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Free convection heat transfer from an inclined heated flat plate in air

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FREE CONVECTION HEAT TRANSFER FROM
AN INCLINED HEATED FLAT PLATE IN AIR

by

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A

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ABSTRACT

An experimental investigation has been performed to determine the free convection heat transfer from a heated flat plate in air moved from the vertical position through three inclined positions to the horizontal position. The hot surface of the plate was facing downward for the horizontal and three inclined positions. Tests were performed at plate surface temperatures from 120°F up to 404°F. Data for the plate surface temperature at about 165°F with the plate in the vertical position agrees very well with previous experimental work. This same data was used to determine a new parameter, introduced into the Pohlhausen free convection boundary layer equation, to account for the angular position of the plate as it is moved from the vertical to the horizontal position. Use of this modified equation results in a convergence of all data to one normalized curve.

ACKNOWLEDGMENTS

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B	New boundary layer parameter, defined as: $[(1 + \cos\lambda)/2](g\beta\theta_s/4\nu^2)^{1/4}$, $ft^{-3/4}$.
C	Arbitrary constant.
c	Boundary layer parameter, defined as: $(g\beta\theta_s/4\nu^2)^{1/4}$, $ft^{-3/4}$.
C_p	Constant pressure specific heat for air, Btu/lb-°F.
g	Acceleration of gravity, ft/hr^2.
h_c	Natural convection heat transfer coefficient of a heated surface in ambient air, Btu/hr-ft^2-°F.
h_{cm}	Mean coefficient of heat transfer by natural convection of a heated surface in ambient air, Btu/hr-ft^2-°F.
k	Thermal conductivity of air, Btu/hr-ft-°F.
L	Plate length from the leading edge to the transition point, in.
N_{Gr_x}	Grashof number: $g\beta\theta x^3/\nu^2$, dimensionless.
N_{Nu_x}	Nusselt number: $h_c x/k$, dimensionless.
N_{Pr}	Prandtl number: $C_p\mu/k$, dimensionless.
q	Heat transfer rate, Btu/hr-ft^2.
T	Air temperature in the thermal boundary layer, °F.
T_s	Plate surface temperature, °F.
T_∞	Free-stream air temperature, °F.
V_x, V_y, V_z	Air velocity components in the x, y, z directions, ft/sec.
X, Y, Z	Coordinate axes.
x	Distance from the plate leading edge, in.
β	Thermal coefficient of volume expansion of air, 1/°F.

θ	Local air temperature difference: $(T - T_{\infty})$, °F.
θ_s	Total temperature difference: $(T_s - T_{\infty})$, °F.
η	Boundary layer variable, defined as: $cy/x^{1/4}$, dimensionless.
η'	New boundary layer variable, defined as: $By/x^{1/4}$, dimensionless.
λ	Angle of the inclined hot surface from the vertical position, degrees.
ρ	Mass density of air, lb/ft^3.
μ	Absolute viscosity of air, lb/ft-hr.
ν	Kinematic viscosity of air, ft^2/hr.
ϕ	Temperature parameter, defined as: θ/θ_s, dimensionless.

INTRODUCTION

Free or natural convection is a fluid flow motion that arises solely as a result of density variation caused by thermal expansion of the fluid in a non-uniform temperature field. It is a natural phenomenon occuring everywhere within the atmosphere of the earth where inequalities of temperature exist. Investigations of free convection in air have been of little interest except to meteorologists or astrophysicists up until the past quarter century. Progress in other applications has been gradual due primarily to two causes. First, the interaction of the dynamics and thermodynamics leads to a rather complex analysis, and second, in most problems of interest, the prime factors governing natural convection, namely the buoyancy force, fluid volumetric expansion coefficient, and the temperature are small.

With the advent of jet propulsion and nuclear power (1)*, the three prime factors governing natural convection can all very greatly exceed their previously considered bounds. Hence, in many practical present-day problems in the field of aeronautics, atomic power, magnetohydrodynamics, electronics and chemical engineering, the natural convection phenomenon can be important. Accordingly, more interest has recently been shown in the natural convection phenomenon.

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*Numbers in parenthesis indicate references listed in the Bibliography.

Heat transfer from a flat plate in free convection is the more basic problem for investigation. A number of research papers have been published, both theoretical and experimental, with the flat plate in two particular positions - vertical and horizontal. Equations and curves based on mathematical analyses and experimental data have been presented for various cases with the flat plate in these two positions. However, there is limited data available on the inclined flat plate.

Thus, it is worthwhile to study free convection on a flat plate inclined at various angles in order to acquire more data in this area. It is the purpose of this investigation to gain an understanding of the effect of angular position on the heat transfer and the critical Grashof number.

LITERATURE REVIEW

Generally, the study of convective-heat transfer can be divided into analytical solutions of the convection equations and experimental investigations. The analytical solution may or may not be an exact mathematical solution. The solution could be the result of an approximate integral or numerical approach.

Possibly the first of the few practicable straightforward solutions of the convection equation under steady-state conditions is due to L. Lorenz (1881, (2)). It deals with the heat transfer from a vertical surface at uniform and constant temperature T_s to a colder gas in contact with it, when gravity is the only force acting on the gas. Lorenz correctly recognized that the gas close to the surface streams straight upwards, and he assumed that the horizontal streams were negligible and that consequently the pressure was constant in a horizontal plane, but changed from one horizontal layer to the next. This is the case of streamline flow on a vertical wall. He further assumed that the environment temperature T_∞ at an infinite distance from the wall was constant and that the properties of gas ρ, μ, c_p and k were independent of temperature. Setting up a heat balance for a differential section of the flowing fluid and integrating, Lorenz obtained the following equation

$$h_{cm} = C\,(g \rho^2 c_p k^3 \theta_s / \mu L T_\infty)^{\frac{1}{4}} \qquad (1)$$

where $C = 0.548$, for air used by Lorenz

This equation was a triumph of the classical theory, having revealed for the first time the complex nature of the coefficient of heat transfer by free convection, h_c, in a form which has been shown to be valid with good approximation through more than half a century.

One particular consequence of this equation is that the rate of heat exchange, q, is proportional to $\Theta_s^{5/4}$. This has been verified in numerous experiments, even with fluids of high Prandtl number. See, for example, the work with liquids by Touloukian, Hawkins and Jakob (1948, (3)).

The derivation of equation (1) will not be given, since more exact solutions are presently known. Nusselt (1909, (4)) directed attention to the fact that, according to experiments with air, the equation becomes less exact at Θ_s below 20°F and fails entirely when Θ_s approaches zero. After that Nusselt (1910, 1915 (5,6)) published two well accepted papers, one devoted to forced convection in tubes and the other to free convection in general, where he seems to have been the first to employ the principle of similarity to the field of heat transfer. Referring to the differential method, Nusselt started from the Fourier's equation of heat conduction, the Navier-Stokes equations for an incompressible fluid and the general energy equation in a moving fluid, and obtained similarity expressions of the form

$$\frac{g_1 \beta_1 \rho_1^2 L_1^3 \theta_{s1}}{\mu_1^2} = \frac{g_2 \beta_2 \rho_2^2 L_2^3 \theta_{s2}}{\mu_2^2} = N_{Gr} \qquad (2)$$

$$\frac{\mu_1 C_{p1}}{K_1} = \frac{\mu_2 C_{p2}}{K_2} = N_{Pr} \qquad (3)$$

These equations showed that there are two dimensionless groups called the Grashof number (N_{Gr}) and the Prandtl number (N_{Pr}), which must have the same value in both systems, if similarity is to exist. Their combined effect results in the functional relationship

$$N_{Nu} = \phi\,(N_{Gr}, N_{Pr}) \qquad (4)$$

Jakob and Hawkins (1942, (7)) by use of the dimensional analysis method found that

$$N_{Nu} = C\,(N_{Gr})^n (N_{Pr})^m \qquad (5)$$

where the constant C and the exponent n and m are determined from experimental results.

More than 40 years after Lorenz's fundamental investigation, a series of new studies of the vertical surface problem began with an investigation by Griffiths and A. H. Davis (1922, (8)). They determined the distribution of velocity and temperature close to a vertical plate by direct measurements, making use of a hot wire anemometer to measure the velocity profile. The surface temperature was kept uniform during the experiment. First of all, using a plate 3 or 4 feet high, they verified Lorenz's result that h increases with the fourth root of the height. This result, as is well known, involves the existence of laminar flow. Employing, further, a plate 9 feet high, the authors found that at a distance of about 1/5 in. from the surface and above a certain height neither the velocity nor the temperature increased any more. They concluded that the strata of air nearest the plate were not themselves carrying away the heat from the upper part of the surface, but merely transmitting it to the outer layers which carried it away.

Avoiding some oversimplifications made by Lorenz, Nusselt and Jurges (1928, (9)) succeeded in essentially improving the theory with their experimental work. Measurements of the field of temperature near a vertical hot plate with very thin thermocouples were first made by Nusselt and Jurges in their experiments, but they could not measure the field of velocity in default of a suitable instrument for these small velocities. The most elaborate improvement, however, is due to E. Schmidt and Beckmann (1930, (10)), in cooperation with Pohlhausen, who found a way to integrate the differential equations set up by these authors. The experimental part of their work consisted in the determination of the velocity and temperature field close to the surface of electrically heated vertical plates of about 5 and

20 in. height. The temperatures were measured by a thermocouple with wires of 0.02 mm diameter. As to the air velocities, E. Schmidt solved this problem with his quartz fibre anemometer shown in Fig. 1, consisting of a straight

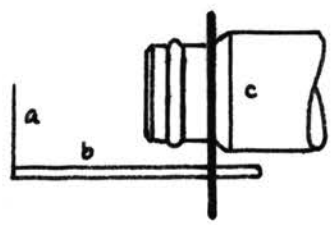

Fig. 1. QUARTZ FIBRE ANEMOMETER BY E. SCHMIDT
a. Quartz fibre
b. Support pin
c. Tube of the microscope

fibre of quartz about 0.02 mm thick, 1 to 2 cm long, fixed at one end, and placed in the field of velocity. This quartz fibre is bent elastically by the flow of air passing it perpendicularly to its length. The deflection of the end of the fibre is measured with the help of a microscope, located several centimeters away from the fibre in order not to disturb the flow where the velocity is measured. The calibration shows that the deflection was not proportional to the velocity. This instrument which allowed for the measurement of air velocity down to a few millmeters per second, enabled E. Schmidt and W. Beckmann to measure the whole field of velocity. Curves of temperature T and vertical velocity v_x in horizontal planes at different heights x above the plate are given in Fig. 2.

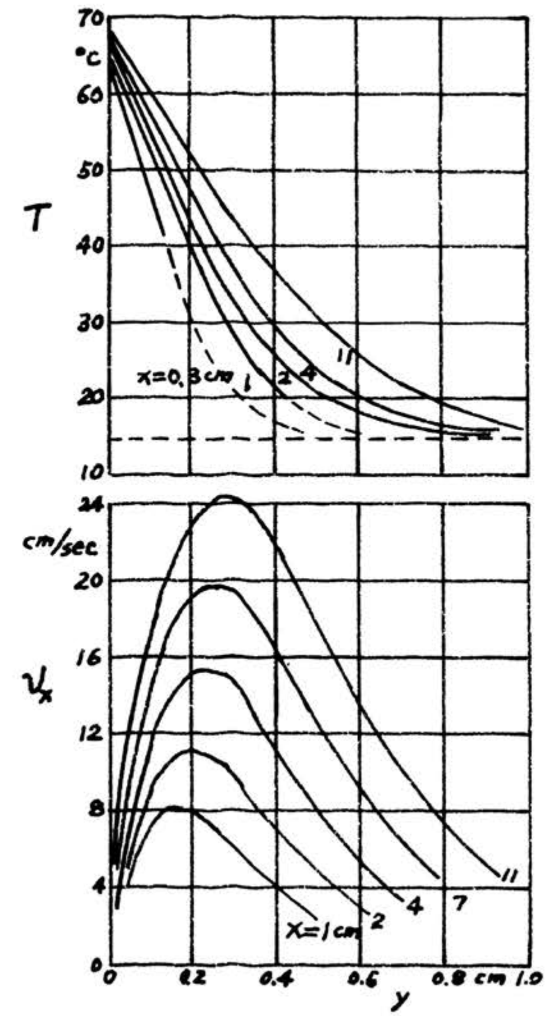

Fig. 2. Horizontal cross section of (a) the field of temperature T and (b) the vertical component v_x of velocity before a vertical plate 12 cm high and heated to about 66 C in air of 15 C, measured at different vertical distances x above the lower edge of the plate (E. Schmidt and W. Beckmann, 1930, (8))

This experiment proved that the hot air motion near a flat plate is confined to a rather thin layer which allows for the simplification of boundary layer theory. Having these experimental results before him, E. Pohlhausen (1930, (10)) found the mathematical solution of the problem.

Pohlhausen introduced instead of the vertical coordinate x and the horizontal coordinate y, the independent variable $cy/x^{\frac{1}{4}}$, where c = 5.885* is a parameter given by the viscosity and buoyancy of air at the plate temperature T_s. The resultant partial differential equations of velocity and temperature change to nonlinear but ordinary ones containing only derivatives up to the third order in the new independent variable. Pohlhausen then obtained

$$\bar{N}_{Nu} = 0.479\left(g\beta\theta_s L^3/\nu^2\right)^{\frac{1}{4}} \qquad (6)$$

Kimball and W. J. King (1932, (12)) through a theoretical investigation, which is based on the observation that the velocity maxima (Fig. 2) occur at places where $\theta=\theta_s/2$, found results which agreed with Schmidt and Beckmann's observations.

Continuing the study R. Weise (1935, (13)) with his experimental work determined valves about 25% higher than Eq. (6). This may be partly due to the influence of the edges and to motions of the ambient air. Schmidt observed that even a small disturbance by any motion around the edges increased the heat transfer by several percentage points.

W. J. King (1932, (14)), Jakob and Linke (1933, (15)) and McAdams (1942, (16)) have obtained curves and equations

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* $c=\left(\frac{g\beta\theta_s}{4\nu^2}\right)^{\frac{1}{4}}$ for air in laminar flow.

to correlate the experimental data. Jakob recommends

$$N_{Nu} = 0.555 \, (N_{Gr} \cdot N_{Pr})^{\frac{1}{4}} \tag{7}$$

for the laminar range where $N_{Gr} \cdot N_{Pr} = 10^4$ to 10^8 and

$$N_{Nu} = 0.129 \, (N_{Gr} \cdot N_{Pr})^{\frac{1}{3}} \tag{8}$$

for the turbulent range where $N_{Gr} \cdot N_{Pr} = 10^8$ to 10^{12}.

R. Weise (1935, (13)) was among the first to measure the temperature distribution on a horizontal plate. He used square aluminum plates, of 16 and 24 cm, 1.0 and 1.5 cm thick, respectively. These plates were suspended in a large room and heated electrically. The results of a total of 70,000 readings were combined to show the different patterns of isothermal lines. One of these patterns is reproduced as Fig. 3. According to these graphs, which vary slightly in

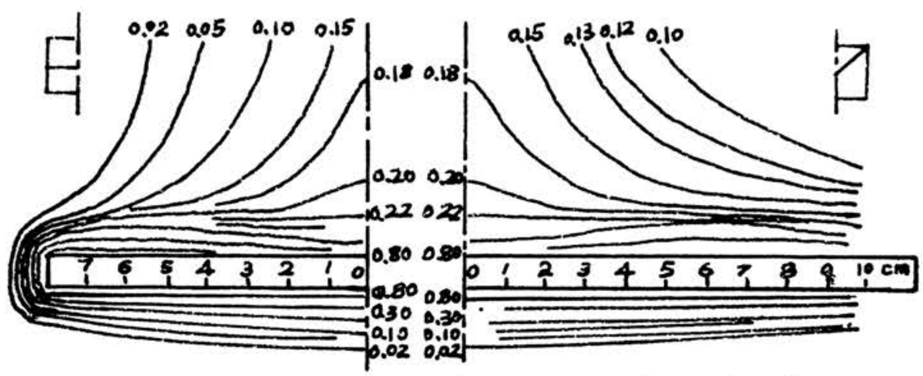

Fig. 3. Isothermals θ/θ_s around a horizontal square plate hanging in air.
θ, θ_s=excess of air and surface temperature, respectively, above air temperature at far distance. Left side of figure: cross section parallel to plate edge; right side of figure: cross section through plate diagonal. From R. Weise (1935, (13)).

different planes through the vertical axis, it is observed that on the bottom side of the plate the boundary layer in which the temperature drop is concentrated is about 1.5 cm thick in the center and 1 cm thick close to the edge. Above the plate cold air is flowing from the edge to the center, causing a depression of the isotherms close to the plate at the center. Weise then calculated individual coefficients of heat transfer from the temperature drop close to the plate, to check the mean coefficient as found by direct measurement and found good agreement. Kraus (1940, (17)) has, in addition, determined the corresponding velocity fields. Below the plate, orderly motion was observed approaching the plate and then moving outward toward the edges. Above the plate, random vortices were noticed. Highest velocities occurred in the vicinity of the edges. The momentum boundary layer on the lower side of the plane exceeded considerably the thermal boundary layer in thickness, even in air with $N_{Pr} = 0.72$.

The largest heat transfer coefficient on a horizontal plate with free convection must be expected to coincide with the highest velocity, i.e., it should occur near the edges. The larger the plate, the smaller the influence of this effect on the entire heat transfer. The overall heat transfer coefficient thus becomes more and more independent of the size of the plate as the plate size increases. A dimensionless relationship of the form $N_{Nu} = C(N_{Gr} \cdot N_{Pr})^{1/3}$

is to be expected. The choice of the characteristic length in the Nusselt and Grashof numbers is thus unimportant, so that either the width or the diagonal or even, as proposed by Weise, the circumference can be used. The measurements of Weise and Krause on plates of 16 by 15 cm to 26 by 26 cm in air and with excess temperatures of the plate ranging from 122 to 662F can be correlated satisfactorily by the equation

$$N_{Nu} = 0.137 (N_{Gr} \cdot N_{Pr})^{\frac{1}{3}} \tag{9}$$

Another method useful in the study of free convection is the optical method. The difference of density and light velocity close to a heated surface can also be used to produce interference fringes. Eckert and Soehnghen (1948, 1951, (18, 19)) used an interferometer to study the mechanism of natural convection and obtained good results.

Y. P. Chang (1957, (20)) has presented his own idea on natural convection. Instead of approaching the problem according to conventional concepts, a short-cut method is introduced by the application of wave motion. Above the heating surface a boundary layer is assumed whose thickness depends upon the heat flow. Inside this layer there is wave motion, stable in the lower part but unstable in the upper. It has been recognized that, if there is a temperature gradient across a stratum of fluid, a wave motion will occur. Each loop of this wave can initiate vortices in the free convection process. Although the calculated results agree excellently with experiments as conducted by previous investigators the theory is still not soundly established.

Although the previous discussion indicates extensive investigation of free convection on vertical and horizontal plates, there has been a limited amount of work done concerning free convection on a flat plate at angles of inclination between the vertical and horizontal.

EXPERIMENTAL WORK

Description of the Apparatus

A picture of the apparatus used in the investigation is shown in Fig. 4, and a schemetic of the function and arrangement of the parts is shown in Fig. 5. To facilitate the study of free convection on the flat plate in various positions the hot surface of this apparatus can easily be moved through all inclined angles with the vertical, from the hot surface upward through the vertical position to the hot surface downward. Heat is supplied at the bottom of the flat plate in an even distribution through the use of electrical resistance heating elements. The plate is large and of sufficient thickness to allow for an even distribution of the heat generated by the resistance elements. When steady state is reached the surface temperature distribution is uniform over the entire plate surface. A movable thermocouple of extremely fine wire at the end of its hot junction was used to record the temperature at predetermined points above the hot surface of the plate.

Test Plate

An aluminum alloy plate was used as the hot surface. Aluminum was used because of its light weight and resultant ease of handling, and because of its high thermal conductivity to allow for a more even temperature distribution in the plate. The dimension of this finished rectangular piece were 26-27/32 in. length, 7 in. width and 11/32 in. thickness.

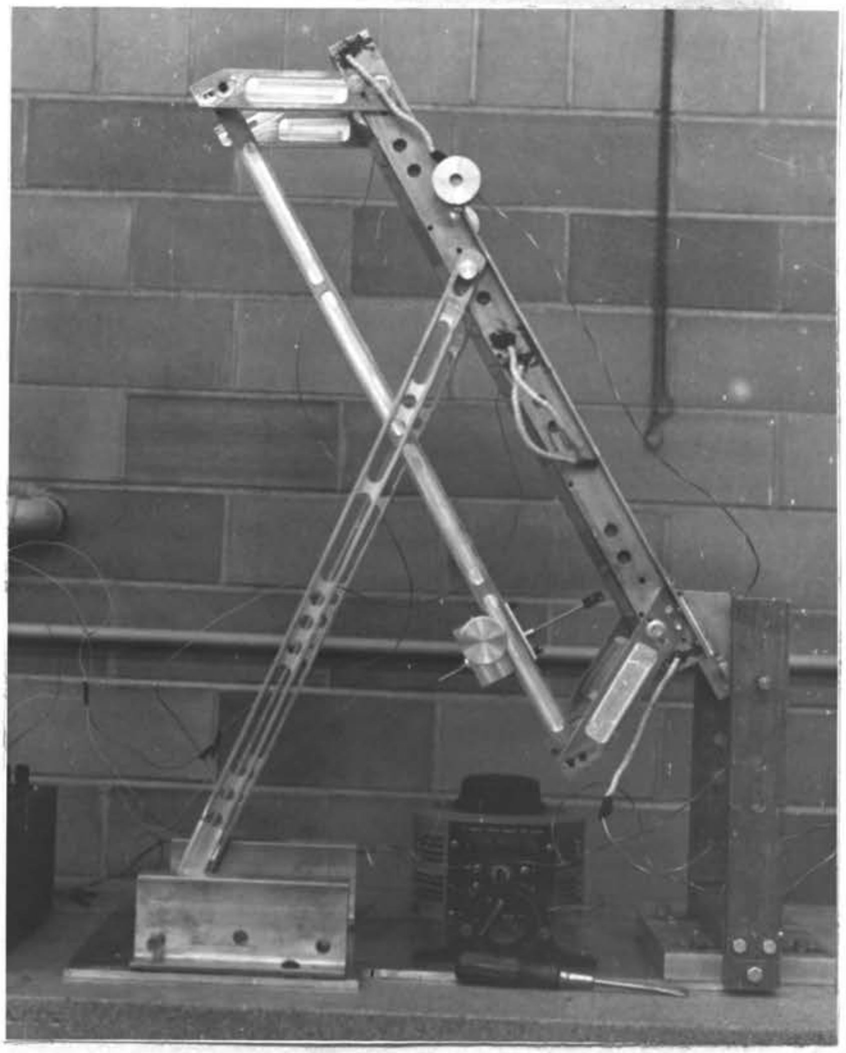

Fig. 4. Experimental Apparatus

KEY to Fig. 5

1. Flat plate (Aluminum alloy)
2. Electrical resistance heating elements
3. Insulating board
4. Special holes in T type aluminum bar of 5/8 in. diameter
5. Supporting bar with threads and nut
6. Hot junction of the detecting thermocouple
7. Micro-motion box
8. Rail
9. Guide bars
10. Autotransformer
11. Movable arms
12. Movable base
13. Potentiometer
14. Ice bath
15. Thermocouple holes
16. Thermocouple wires
17. Frame
18. Base

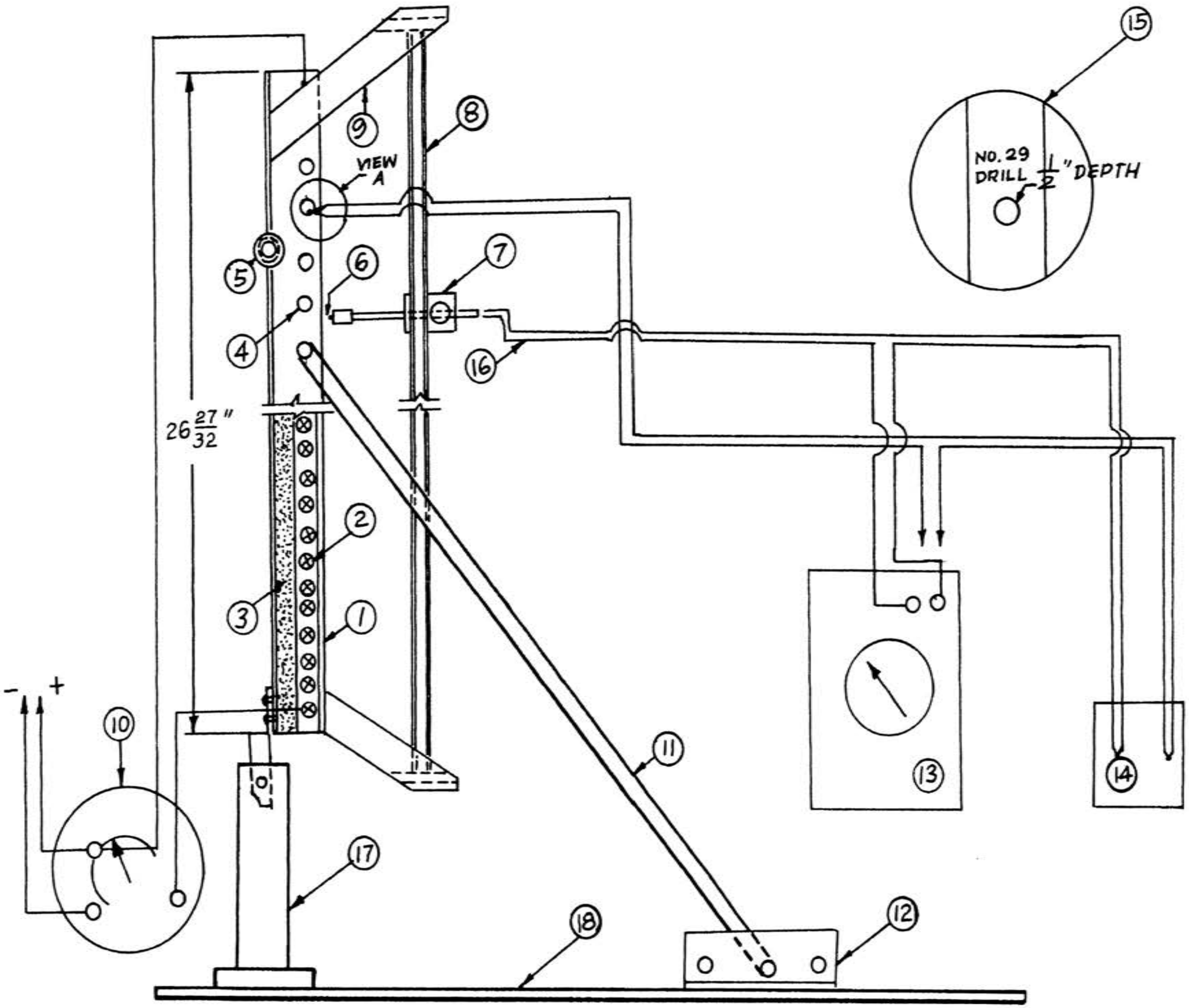

Fig. 5. Schematic of the Apparatus

The hot surface exposed to the air was super-finished to a flat tolerence of ± 0.002". Four equally spaced holes were drilled in each side edge of the plate to allow for insertion of thermocouples.

Power Supply

The heating elements were located at the bottom of the aluminum plate. Ten electrical resistance elements were employed. A large number of holes were drilled in the T-type aluminum guide bars and the adjacent transite insulating bar to provide flexibility in the hook-up of the resistance elements to the power supply. The heater elements can be series connected, parallel, or parallel and series connected as necessary to achieve the desired temperature level*. A variable autotransformer was used to control the power supplied to the resistance elements and thus control the temperature. A 7/8" thick insulating board was located below the electrical heating elements to limit the heat flow in this direction. On both side edges of the aluminum plate were two 1/2 in. thick transite plates also used for insulation. Two T-type aluminum bars were employed to support the plate and these insulators.

Detecting Thermocouple

As shown in Fig. 6, a No. 28 gage B & S copper-constantan thermocouple was used to measure the temperature in the

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*See Appendix 1(A)

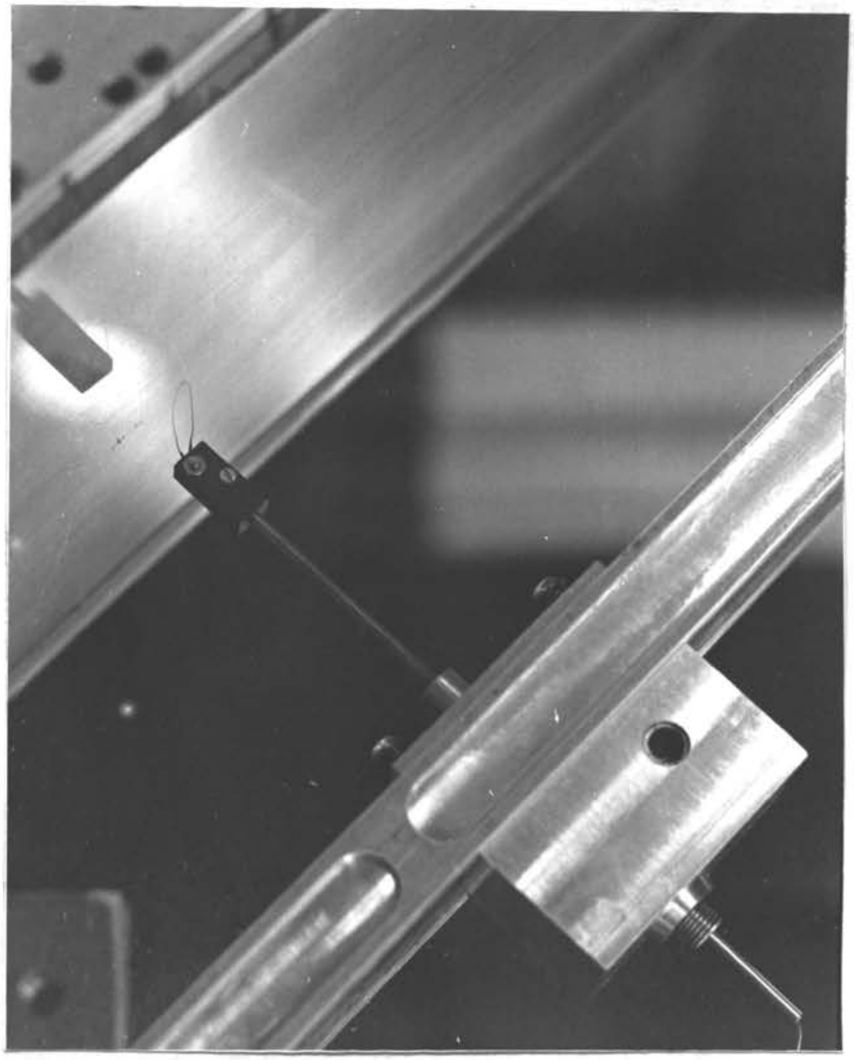

Fig. 6. Micro-Motion Box

free convection thermal boundary layer. The copper and constantan wires were ground to less than 0.002 in. in diameter at their ends and joined by mercury solder with the junction diameter reduced to less than 0.004 in. The influence of the insertion of this extremely fine thermocouple into the thermal boundary layer is negligible*. Its sensitivity is also sufficient to accurately determine the temperature profile within the thermal boundary layer.

This thermocouple was held by a stainless steel tube of 3/16 in.O.D. The thermocouple was attached to the end of the tube by a plastic bracket. The material of which the bracket is made has good insulating characteristic throughout a large temperature range. This rigid mounting of the thermocouple and plastic bracket to the stainless steel tube prevented any motion in the sensing element of the thermocouple. The steel tube was inserted into the motion-screw of the micro-motion box with a force fit. The micro-motion box contains a worm and gear set to obtain a very small displacement of the thermocouple for each revolution of the dial. Each turn of the dial results in a displacement of 29.8/10,000 in. of the thermocouple. The dial is divided into eight divisions, so that the smallest displacement of the thermocouple is 3.6/10,000 in. (See Fig. 4 and Fig. 5). The micro-motion box was moved along two I-beam aluminum rails. The micro-motion box was easily adjusted to any

*See Appendix 1(B)

desired position along the length and width of the plate.

Two thermocouples (24 gage, B & S iron-constantan) were used to detect the plate temperature at eight positions, four on each side edge of the plate (Item 15, Fig. 5). A pair of bars with several slots cut along their length were used to adjust the position of the aluminum plate. A movable base was also employed to allow for more adjustment of the flat plate.

ANALYSIS OF THE EXPERIMENTAL RESULTS

The experimental data were obtained in the span of a month including calibration of the thermocouples and checking results at the same distance, x, from the plate leading edge, moving the thermocouple probe in a transverse direction to insure data reliability (see Fig. 7). Approximately 3000 data points were obtained.*

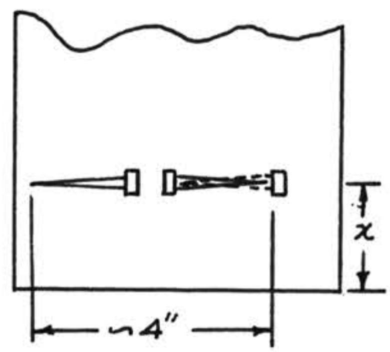

Fig. 7. Thermocouple Traverse

The first curve plotted from the data (Fig. 9) is that of temperature variation through the boundary layer as a function of the perpendicular distance from the plate for the plate in the vertical position (λ =0°)**. This one curve is plotted in this way to show the usual form of temperature distribution in the boundary layer. The remaining curves (Figs. 10 to 16) are plotted so as to normalize the results. Only one set of data was taken in the vertical position since many experiments have already been performed with the plate in this position. It was the object here

*The data are in Appendix 2(A)

**The curves are in Appendix 2(B)

only to compare the data taken in this present investigation with previous work to determine any error in the methods used. The results were in very good agreement with the experimental work of E. Schmidt (1930, (10)). However, when the present data are compared to that of Weise (1933, (13)), this present data are approximately 25 per cent lower.* Fig. 10 shows the data for the vertical plate case including some of the data from Schmidt for comparison.

Next, a new variable was introduced as suggested by E. Pohlhausen in E. Schmidt's paper (1930, (10)) of the form

$$c = (g\beta\theta_s/4\nu^2)^{\frac{1}{4}} \qquad (10)$$

By changing the units into British units the constant c becomes 11.8 instead of 5.865 as in Schmidt's work. The results are in excellent agreement with both E. Pohlhausen's mathematical analysis and E. Schmidt's experimental work. Fig. 10 of Appendix 2(B) shows this result. It is apparent that equation (6) from the Literature Review, developed by E. Schmidt, is still recommended by the author's work for a flat plate in the vertical position with free convection in air. This equation is

$$\overline{N_{Nu}} = 0.479\,(N_{Gr})^{\frac{1}{4}} \qquad (11)$$

During the experiment the author found that the profile

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*See the Literature Review.

of the temperature gradient in the boundary layer of the flat plate in an inclined position is not as first imagined. Instead of a thick boundary layer as a result of the plate inclination, there exists a thin layer along the surface of the hot plate in both the laminar and turbulent flow regions. Consider a small element dv in this boundary layer with the buoyant force given by ($g\rho\beta\theta$) resolved into two components, one along the hot surface and the other perpendicular to the hot surface, as shown in Fig. 8. The only effective force of the fluid flow is ds which is along the hot surface and is equal to ($g\rho\beta\theta$) $\cos\lambda$. If the temperature is not too high (in this experimental investigation a temperature dif-

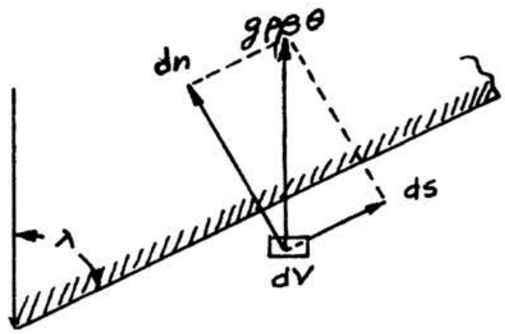

Fig. 8. Buoyancy Forces on the Inclined Plate

ference of over 350°F resulted in an unstable thermal boundary layer) the air flow will be laminar near the leading edge and some distance along the plate and will then pass through a transition stage and finally become turbulent.

In 1960 F. Kreith (1960, (21)) considered the inclined plate and inserted cos λ into the equation given by E. G. R. Eckert (1948, (22)) for free convection from a heated vertical plate. This new equation then becomes

$$\bar{N}_{Nu} = 0.508 \left[N_{Pr}^{2} / (0.952 + N_{Pr}) \right]^{\frac{1}{4}} \cdot \left(\frac{g \beta \theta_s \cos\lambda \, x^3}{\nu^2} \right)^{\frac{1}{4}} \quad (12)$$

It is apparent in equation (12) that as the angle, λ , approaches 90°, the Nussult number, N_{Nu}, approaches 0, which means that in the horizontal position no heat is transferred by free convection. It becomes obvious, then, that the interaction of the dynamics and thermodynamics of the fluid must be considered before a valid relationship can be obtained for Nusselt number as a function of the flat plate angular position.

In Fig. (10) through (15) are shown the results of the inclined plate tests. The abscissa is the geometry parameter, $11.8y/x^{*}$, and the ordinate is the dimensionless temperature ratio, θ/θ_s. Plotted in this way the data for a given angle of inclination, λ , with different height, x, above the leading edge of the heated plate forms a single curve. The slope of the curve, $d\phi/d\eta$, decreases as the angle of inclination, λ, increases, as shown in the comparison curve, Fig. 15. Several attempts were made to attain a new variable to transform this family of curves represented in Fig. 15 into one curve. Multiplying the coefficient, c, given by equation (10) by the expression $\left(\frac{1 + \cos\lambda}{2}\right)$ results in a convergence of the family of curves shown in Fig. 15 to a single curve, as shown in Fig. 16. Thus, the new coefficient, B, becomes

$$B = [(1 + \cos \lambda)/2] \cdot (g\beta \theta_s / 4\nu^2)^{\frac{1}{4}} \tag{13}$$

From equation (13) it can be seen that for the vertical plate ($\lambda = 0°$), the coefficient reduces to the value given by equation (10), and for the horizontal plate ($\lambda = 90°$), the coefficient becomes one-half the value given by equation (10). For comparison, McAdams (1954, (24)) recommends, for a horizontal heated plate facing downward, an equation of the form

$$\bar{N}_{Nu} = C\,(N_{Gr} \cdot N_{Pr})^{\frac{1}{4}} \tag{14}$$

In this equation, C is a constant which takes on the average value of 0.26. With the Prandtl number for air taken as 0.733, and the constant C of 0.26, equation (14) then becomes

$$\bar{N}_{Nu} = 0.24\,(N_{Gr})^{\frac{1}{4}} \tag{15}$$

For the case of a vertical heated plate E. Schmidt (1930, (10)) recommends equation (11) of the form

$$\bar{N}_{Nu} = 0.479\,(N_{Gr})^{\frac{1}{4}} \tag{11}$$

Thus, equations (15) and (11) for the horizontal and vertical heated plates differ only in the constant. The constant in the horizontal case is approximately one-half that of the vertical. This condition is satisfied by the choice of the coefficient, B, given by equation (13).

As discussed earlier, E. Pohlhausen has determined a solution to the incompressible continuity, momentum, and energy equations which is applicable to the free convection thermal boundary layer problem. Rather than repeat the solution here, reference is made to the development contained, for example, in Schlichting (1960, (24)), Chapter XIV. Briefly, Pohlhausen demonstrated that if a stream function is introduced by putting $v_x = \frac{\partial \psi}{\partial y}$ and $v_y = \frac{\partial \psi}{\partial x}$ then the resulting partial differential equations for ψ can be reduced to two ordinary differential equations by the similarity transformation

$$\eta = c\, y/(x)^{\frac{1}{4}} \tag{16}$$

$$\psi = 4 \nu c\, x^{\frac{3}{4}} f(\eta) \tag{17}$$

where

$$c = (g \beta \theta_s / 4 \nu^2)^{\frac{1}{4}} \tag{10}$$

The temperature distribution in the free convection boundary layer is determined by the function $\phi(\eta)$ where ϕ is θ/θ_s. Thus, since $\eta = cy/x^{\frac{1}{4}}$, then the non-dimensional temperature distribution in the boundary layer, θ/θ_s, is a function of $y/x^{\frac{1}{4}}$. For an assumed Prandtl number of 0.733 for air, it can be seen in Fig. 10 that the experimental results of this investigation for the plate in the vertical position agree very well with the Pohlhausen development.

Substituting the new parameter, B, given by equation (13), for c in equation (16), results in a new expression for η' of the form

$$\eta' = B\,y/x^{\frac{1}{4}} \qquad (18)$$

Now, the non-dimensional temperature distribution in the boundary layer θ/θ_s, is a function of $y/x^{\frac{1}{4}}$ and the plate inclination, λ . With a Prandtl number for air of 0.733, the experimental results of this investigation for all inclined angles agree with the modified Pohlhausen development given by equation (18). This is shown in Fig. (10) to (14).

With the temperature distribution known, the quantity of heat transferred per unit time and area from the flat plate to the fluid at section x is given by

$$q(x) = -k\left(\frac{\partial T}{\partial y}\right)_{y=0} = h_c\,\theta_s \qquad (19)$$

Equation (19) indicates that the heat is transferred from the plate to the fluid by conduction through a very thin layer adjacent to the plate. Using the above development, the temperature gradient at the wall, $(\partial T/\partial y)_{y=0}$, is determined to be

$$\left.\frac{\partial T}{\partial y}\right)_{y=0} = \left.\frac{\partial T}{\partial \phi}\right)\cdot\left.\frac{\partial \phi}{\partial \eta}\right)_{\eta=0}\cdot\left.\frac{\partial \eta}{\partial y}\right) \tag{20}$$

For a Prandtl number for air of 0.733, $\partial\phi/\partial\eta)_{\eta=0} = -0.508$, thus

$$\left.\frac{\partial T}{\partial y}\right)_{y=0} = -0.508\,\theta_s B x^{-\frac{1}{4}} \tag{21}$$

and q becomes

$$q(x) = 0.508\,k\,\theta_s B x^{-\frac{1}{4}} = h_c\,\theta_s \tag{22}$$

The local heat transfer coefficient on a flat plate at some position x is then given by

$$h_c = 0.508\,k\,B\,x^{-\frac{1}{4}} \tag{23}$$

where B is defined by equation (13) as

$$B = [(1+\cos\lambda)/2]\cdot(g\beta\theta_s/4\nu^2)^{\frac{1}{4}} \tag{13}$$

Since the local value of the Nusselt number, N_{Nu_x}, is given by

$$N_{Nu_x} = h_c x/k \tag{24}$$

then equation (23) can be written in the form

$$N_{Nu_x} = 0.36\,[(1+\cos\lambda)/2]\cdot(N_{Gr_x})^{\frac{1}{4}} \tag{25}$$

where N_{Gr_x} is the local Grashof number at the position x, given by

$$N_{Gr} = (g\beta\,\theta_s\, x^3/\nu^2) \tag{26}$$

Equation (25) can be used to determine the value of the local free convection heat transfer from a heated flat plate at any angle of inclination, λ , from the vertical through the horizontal, the hot surface of the plate facing downward in the horizontal and inclined positions.

The heat transferred from a flat plate of unit width and length L per unit time is given by

$$Q = \int_0^L q(x)\,dx = 0.677k\,\theta_s B L^{\frac{3}{4}} = h_{cm}\,\theta_s \tag{27}$$

Thus, the mean heat transfer coefficient, h_{cm}, becomes

$$h_{cm} = 0.677\,k\,B\,L^{\frac{3}{4}} \tag{28}$$

where B is defined by equation (13) as

$$B = [(1+\cos\lambda)/2]\cdot(g\beta\,\theta_s/4\nu^2)^{\frac{1}{4}} \tag{13}$$

Since the average value of the Nusselt number, $\overline{N}_{Nu}$, is given by

$$\overline{N_{Nu}} = h_{cm}L/k \tag{29}$$

then equation (28) can be written in the form

$$\overline{N_{Nu}} = 0.48\,[(1+\cos\lambda)/2]\cdot(N_{Gr})^{\frac{1}{4}} \tag{30}$$

where N_{Gr_L} is the Grashof number for the plate of length L from the leading edge to the transition point, given by

$$N_{Gr_L} = \left(g \beta \theta_s L^3 / \nu^2 \right) \qquad (31)$$

Equation (30) can then be used with good accuracy to determine the laminar free convection heat transfer from a heated flat plate for any angle of inclination, λ , from the vertical through the horizontal, the hot surface of the plate facing downward in the horizontal and inclined positions.

DISCUSSION AND RECOMMENDATIONS

It was the primary object of this investigation to attain a solution for free convection heat transfer from a heated flat plate in the vertical and horizontal positions, and three inclined positions between the vertical and horizontal. The hot surface of the plate was facing downward for the horizontal and three inclined positions. The original plan was to study the mechanism of free convection through direct temperature measurement in the thermal boundary layer using a thermocouple, and through the use of a modified Schlieren system to get a picture of the temperature gradient in the thermal boundary layer. This latter method was abandoned after more than a month of trying to adapt an existing modified Schlieren system to fit the needs of this investigation. Further, the original plan called for a measurement of the velocity profile in the boundary layer through the use of a quartz fibre.* However, such an arrangement could not be obtained so no velocity measurements were made. A more complete picture of the free convection heat transfer problem could have been obtained had it been possible to measure the velocity profile in addition to the temperature profile through the boundary layer.

The data plotted in Fig. 9 through 16 came from plate surface temperatures, T_s, ranging from 150°F to 170°F. These

*See the Literature Review.

data are the most reliable and are comparable to that of Schmidt (10) Weise (13), and others. In the case of the plate surface temperature of approximately 120°F, the difference between the ambient temperature and the plate temperature is small. Any variations in the room temperature would then exert a substantial influence on the results obtained for temperature in the boundary layer. Thus, it is important to be able to control the ambient temperature in order to prevent this effect on the results.

The data obtained for plate surface temperatures in the range of 300°F to 400°F were likewise inconsistent. Large fluctuations resulted from small disturbances in the system which prevented a thorough investigation in the higher temperature range. If the modified Schlieren system could have been adapted to this investigation, then it is believed that this inconsistency in the thermocouple readings could have been explained.

Near the leading edge of the flat plate (within about 1 inch), the thermal boundary layer was difficult to determine. Schmidt (10) noted this difficulty in his work on heated vertical plates. It is believed that the low value of the momentum, ρv, resulting from the low air velocity, v, at the plate leading edge results in a flow condition which is easily influenced by local disturbances. As soon as the air has accelerated some short distance up the plate, its momentum has increased. The flow then becomes more stable and is less influenced by local disturbances.

It is recommended that equation (30) be used to determine the average value of the laminar free convection heat transfer from a heated flat plate at any angle of inclination from the vertical through the horizontal. The hot surface of the plate faces downward in the horizontal and inclined positions. Equations (30) and (31) are repeated here

$$\bar{N}_{Nu} = 0.48[(1+\cos\lambda)/2]\cdot(N_{Gr_L})^{1/4} \tag{30}$$

where N_{Gr_L} is the Grashof number for the plate of length L from the leading edge to the transition point, given by

$$N_{Gr_L} = (g\beta\,\theta_s L^3/\nu^2) \tag{31}$$

For the smooth flat plate in the vertical position the laminar flow region extends to a plate length of 12 in. with a corresponding Grashof number of 4.0×10^8. In the horizontal position, hot surface downward, the upper limit on the Grashoff number for the tests was 3.0×10^{10}. For the intermediate inclined positions of λ = 30°, 45° and 60°, the laminar flow extends to a plate length of 14 in., 18 in. and 20 in., respectively. This corresponds to Grashoff numbers of 6.4×10^8 for 30° inclination, 1.4×10^9 for 45° inclination, and 1.9×10^9 for 60° inclination.

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VITA

The author, Shu Chien Yung, was born on November 13, 1936 in Chengdo, China. He received both his high school and college education in Taipei, Taiwan, China. A Bachelor of Science degree in Mechanical Engineering was received from National Taiwan University in June 1959. After graduation the author served in the Chinese Air Force for one and a half years. Upon discharge in February 1961 he accepted employment with the China Textile Industrial Corporation.

In October of 1963, the author left for the United States to continue his studies by working towards the degree of Master of Science in Mechanical Engineering at the University of Missouri at Rolla.

APPENDIX 1

(A) Power Supply

The power supply for heating the flat plate in this investigation used a variable transformer supplying energy to the heating elements connected in series. The author found that the temperature distribution was good for most temperature ranges investigated. Thus, the special arrangement of parallel or series-parallel for the heater elements was not needed.

(B) Detecting Thermocouple

a. In 1931 E. Schmidt also used a thermocouple in his experimental work. His thermocouple of 0.02 mm diameter was considered small enough to make its presence in the boundary layer of no effect.

b. Several configurations were tried before a satisfactory arrangement was realized for the detecting thermocouple. First, the thermocouple probe was made by using a fine circular ceramic tube of special design (Fig. a), having two small holes inside the tube for insertion of the thermocouple wires. Data were taken at the surface using this device and compared with the plate temperature indicated by the thermocouple inserted in the holes located along the plate edge. The correlation was not good. Temperatures were also determined in the thermal boundary layer using this device and the data compared with E. Schmidt and Eckert's (1948, (18)) data. Again, the comparison was not

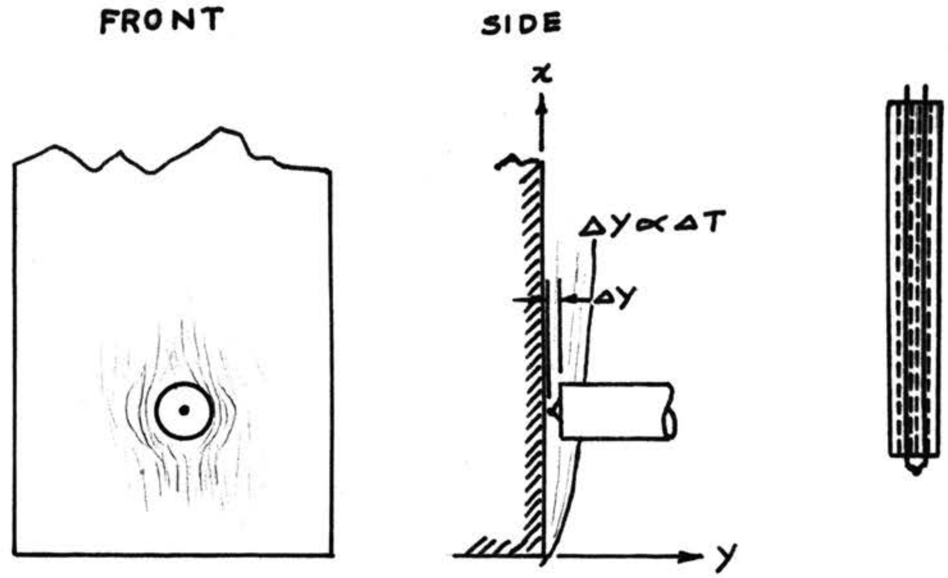

Fig. a

good. It is the opinion of the author that this arrangement results in a large conduction error because the temperature in the Y direction is large, and because the disturbance in the boundary layer is considerable. Moreover, the motion of the thermocouple was difficult to control because of the lack of physical support for the ceramic insulator which holds the thermocouple wires. Other attempts were made to achieve a satisfactory arrangement with the final device used in the investigation shown in (Fig. b). Here the thermocouple was attached to a small rectangular plastic piece, with the extremely fine thermocouple wires extending parallel to the hot surface and the plate leading edge to

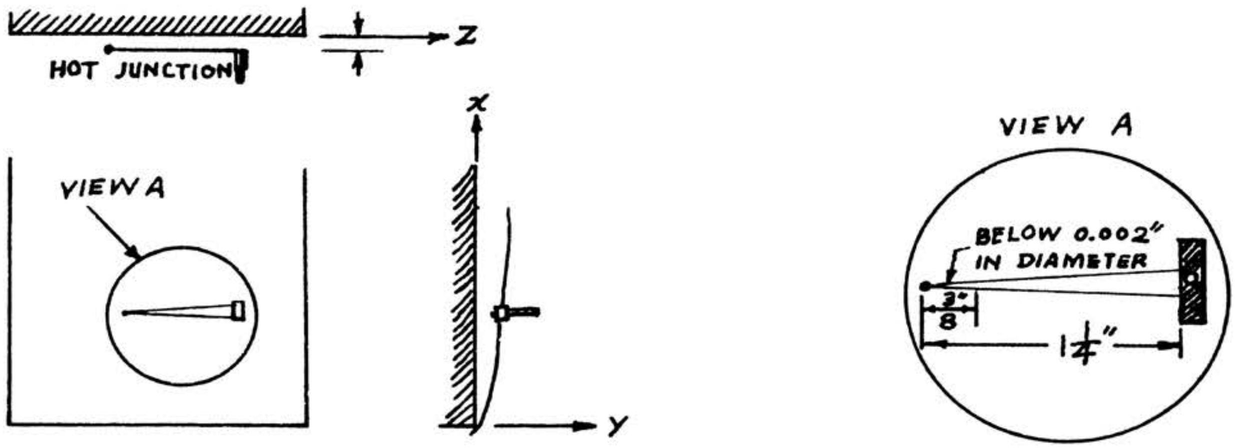

Fig. b

reduce the conduction error along the thermocouple wires. With the temperature assumed constant in the Z-direction, we can say that the temperature of the hot junction is the same as the temperature of that point which it occupies, and there is no conduction error present. Further, because of the small size of the junction and wires, there is negligible influence due to the presence of the thermocouple in the boundary layer.

APPENDIX 2: Test Procedure

Only the important steps required in the test procedure are listed here.

1. The plate was heated by selecting the appropriate voltage setting on the variable transformer to allow electrical energy to flow through the resistance heaters. A period of from two to three hours was necessary to allow the plate to reach a steady state temperature condition before data could be taken.

The steady state condition was determined by monitoring the eight thermocouples inserted in holes located in the side edges of the flat plate (see Fig. 5). When there was no change in the thermocouple reading for a period of from twenty to thirty minutes, it was assumed that the plate had reached a steady state condition.

2. An ice bath was prepared and used as the cold-junction reference temperature.

3. The barometric pressure and room temperature were recorded.

4. The thermocouples were calibrated at two points: the boiling point of water; and room temperature, comparing the thermocouple with a calibrated thermometer.

5. The detecting thermocouple was positioned at a pre-

determined point. The emf indicated on the potentiometer was recorded and later converted to temperature. The detecting thermocouple was then moved through the boundary layer at selected points along the plate and the above process repeated.

6. The procedure indicated in Item 5 above was repeated for each angular position of the plate and each plate temperature condition.

APPENDIX 3(A)

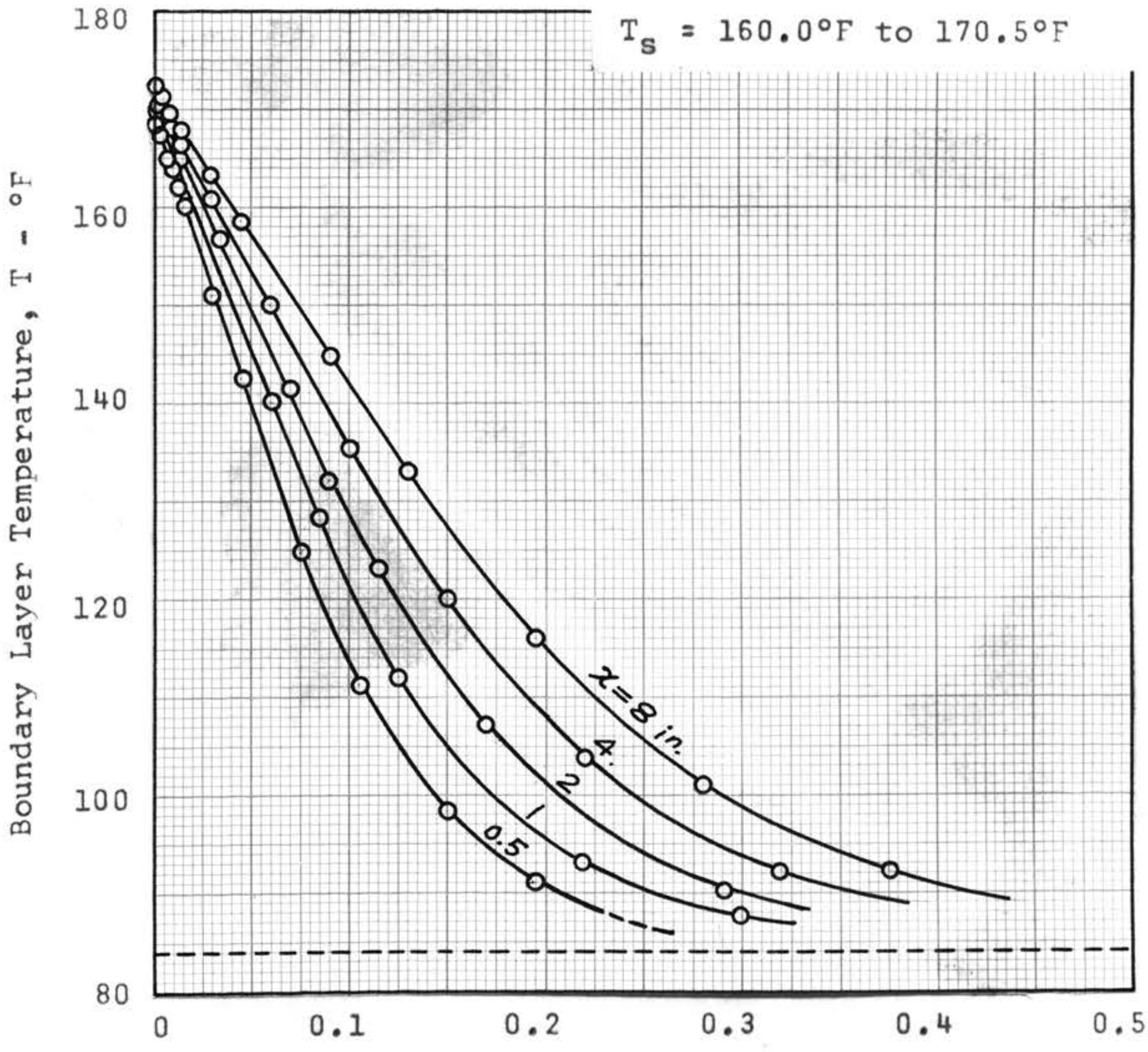

Fig. 9. Boundary Layer Temperature Profile on a Vertical (λ = 0°) Flat Plate in Air

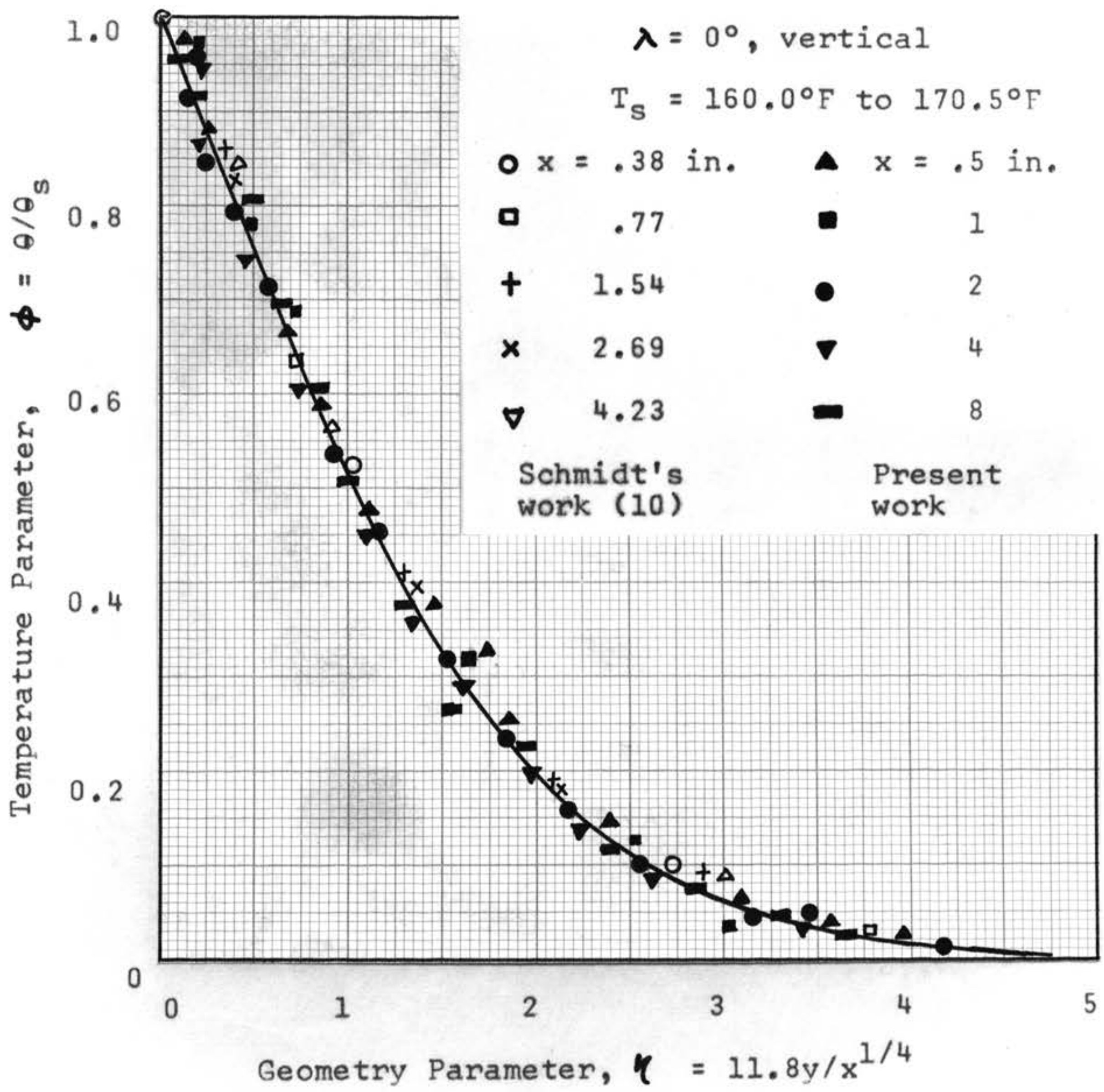

Fig. 10. Dimensionless Temperature Profile for Laminar Free Convection on an Inclined Flat Plate for $\lambda = 0°$, Vertical

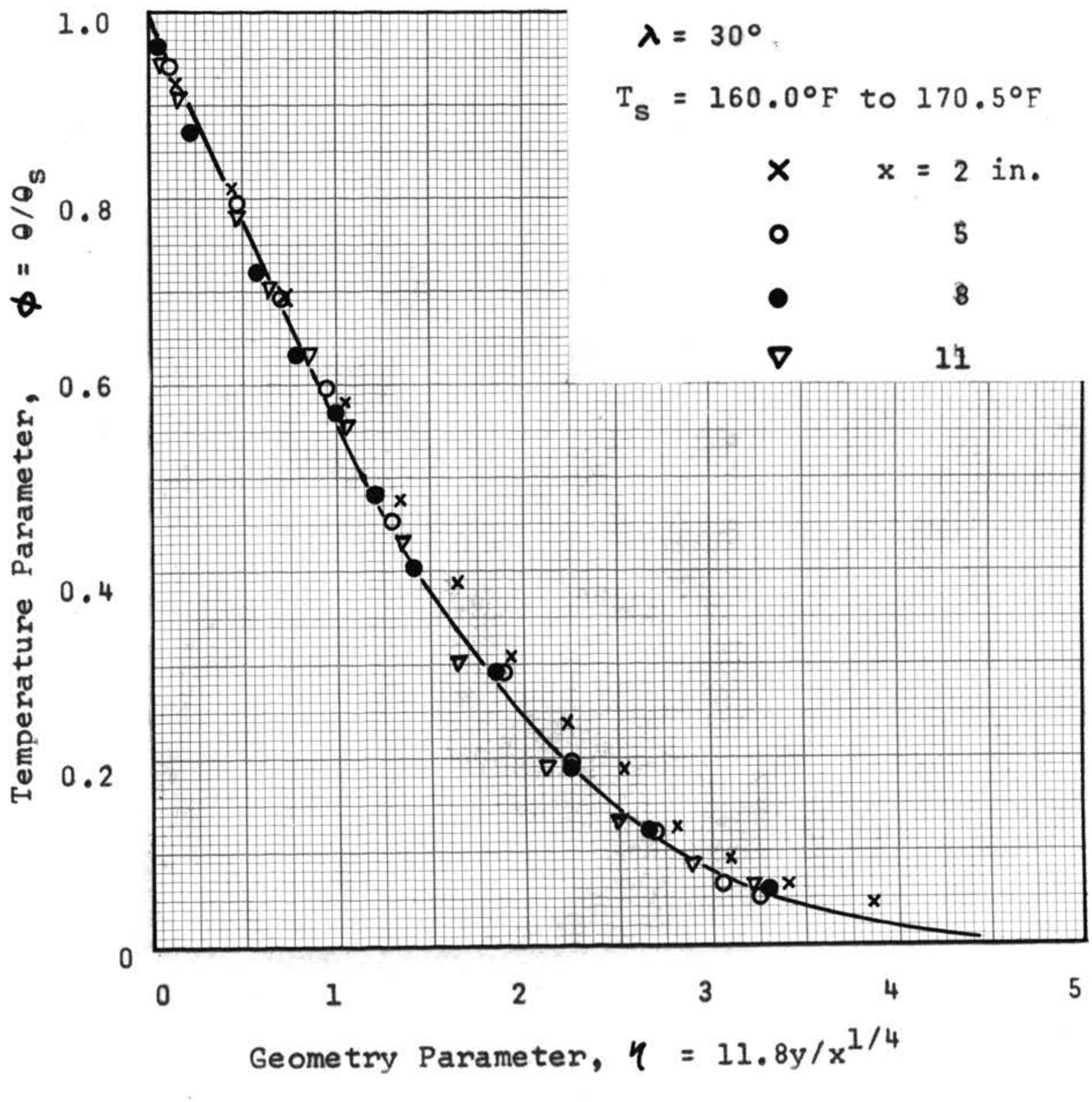

Fig. 11. Dimensionless Temperature Profile for Laminar Free Convection on an Inclined Flat Plate for $\lambda = 30°$

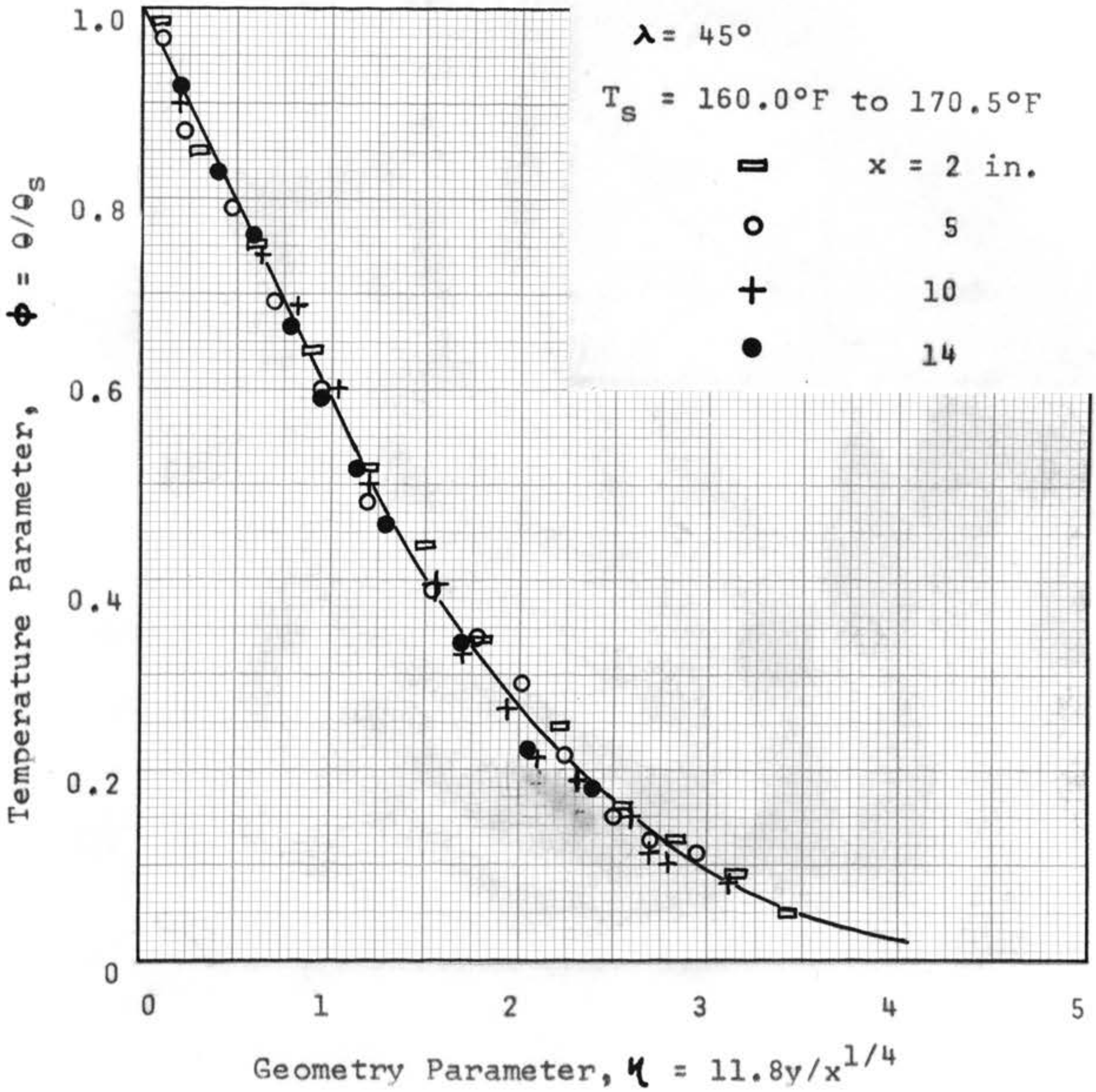

Fig. 12. Dimensionless Temperature Profile for Laminar Free Convection on an Inclined Flat Plate for $\lambda = 45°$

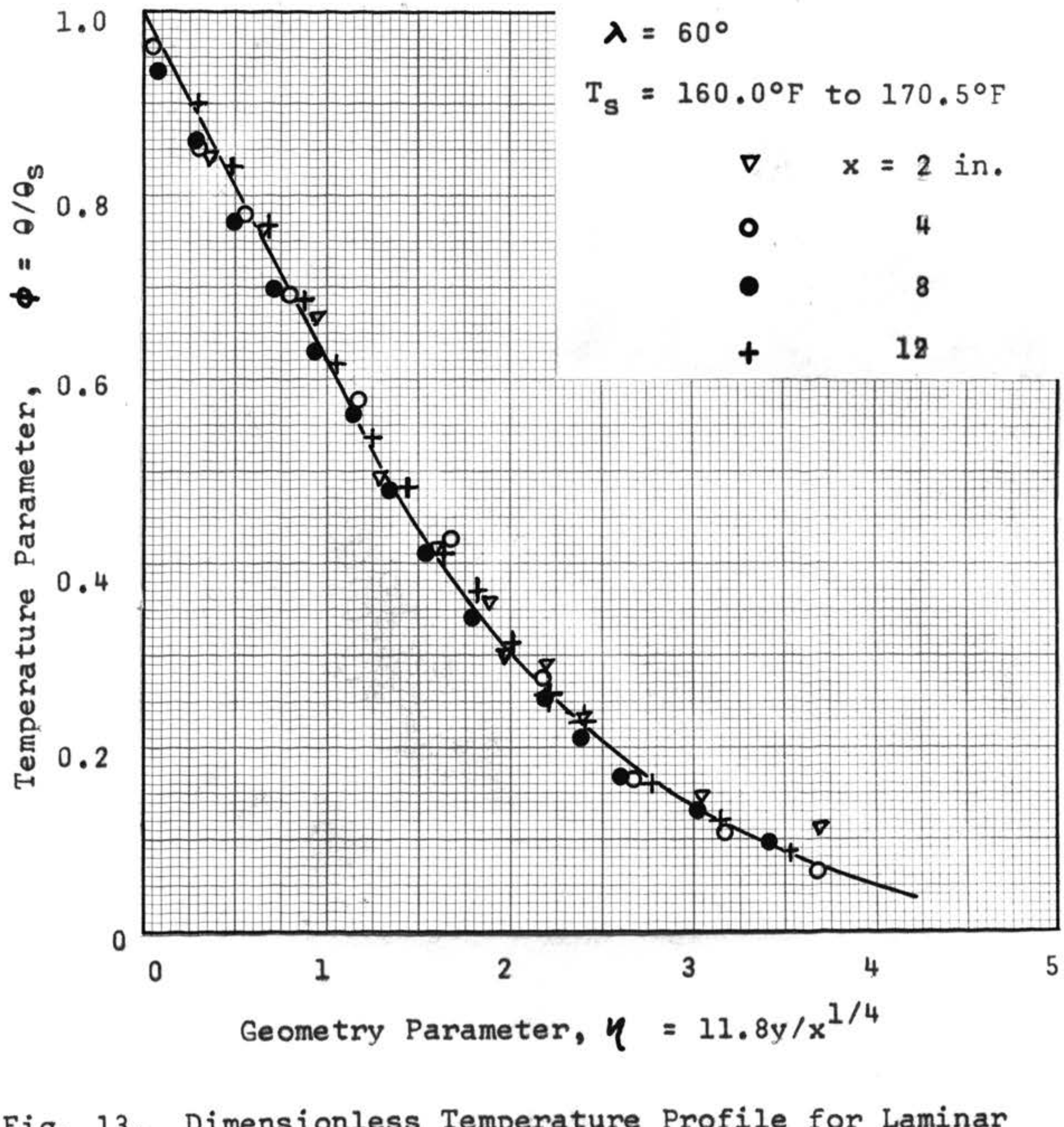

Fig. 13. Dimensionless Temperature Profile for Laminar Free Convection on an Inclined Flat Plate for $\lambda = 60°$

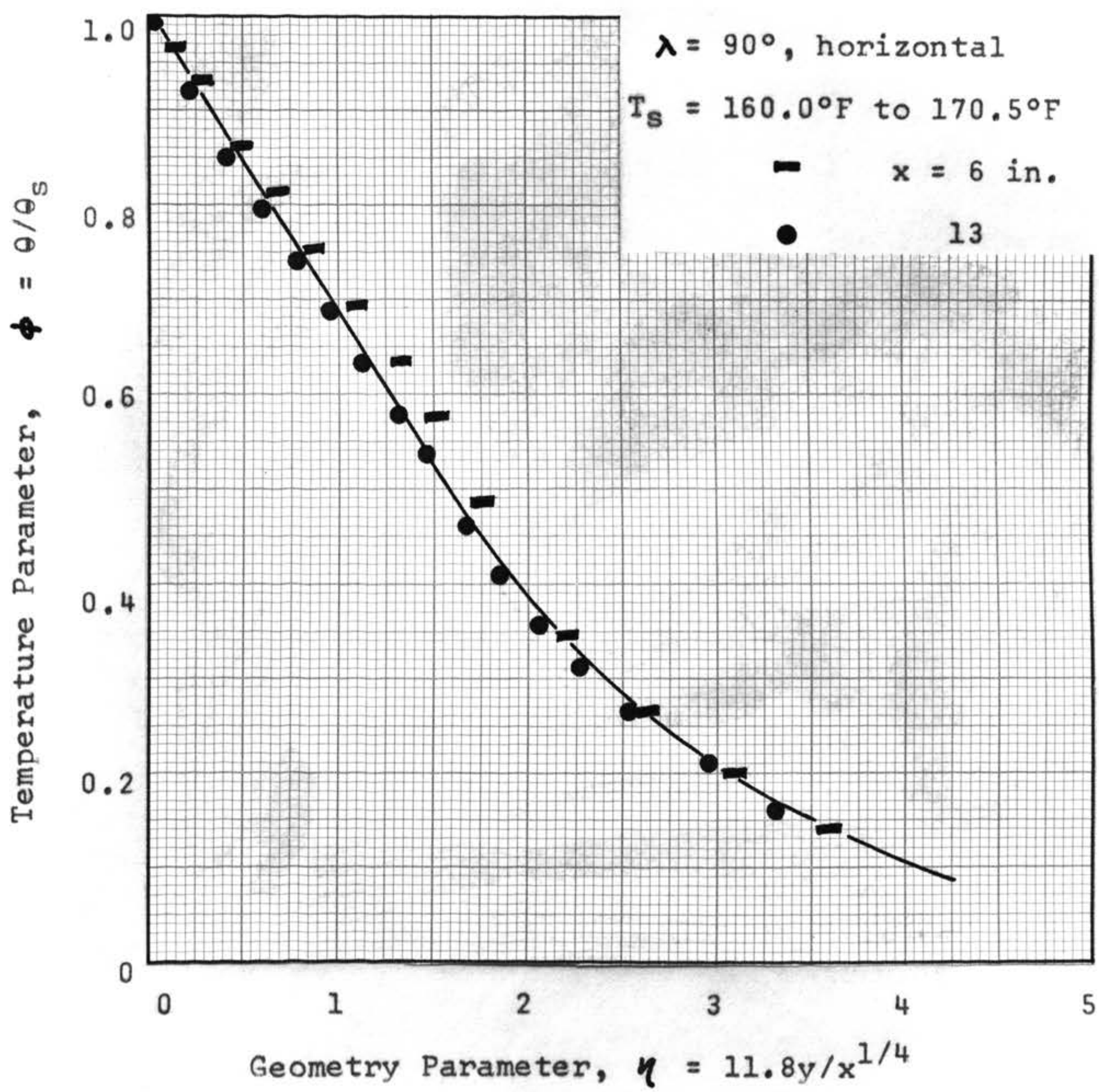

Fig. 14. Dimensionless Temperature Profile for Laminar Free Convection on an Inclined Flat Plate for λ = 90°, Horizontal

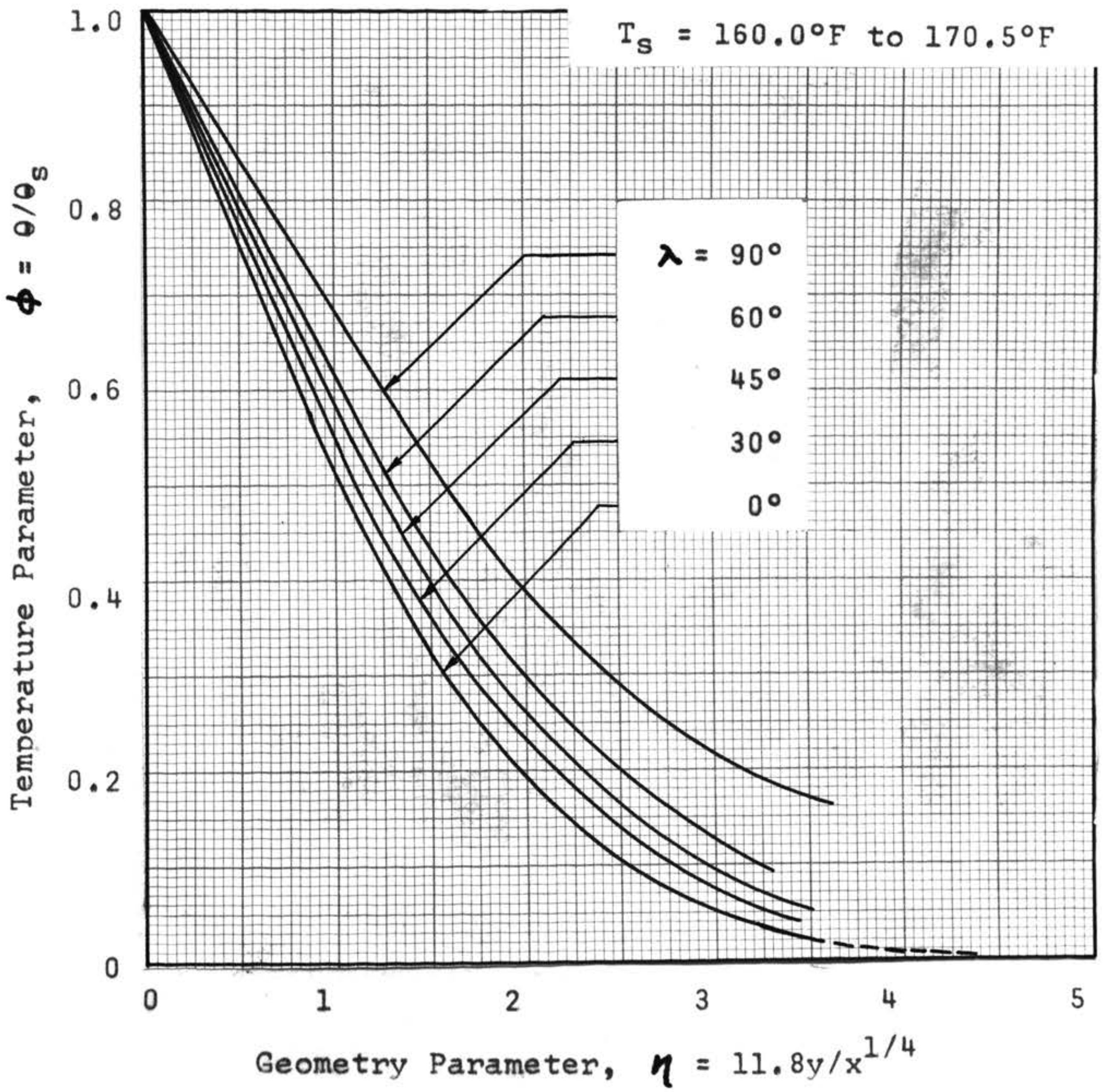

Fig. 15. Dimensionless Temperature Profile for Laminar Free Convection on an Inclined Flat Plate

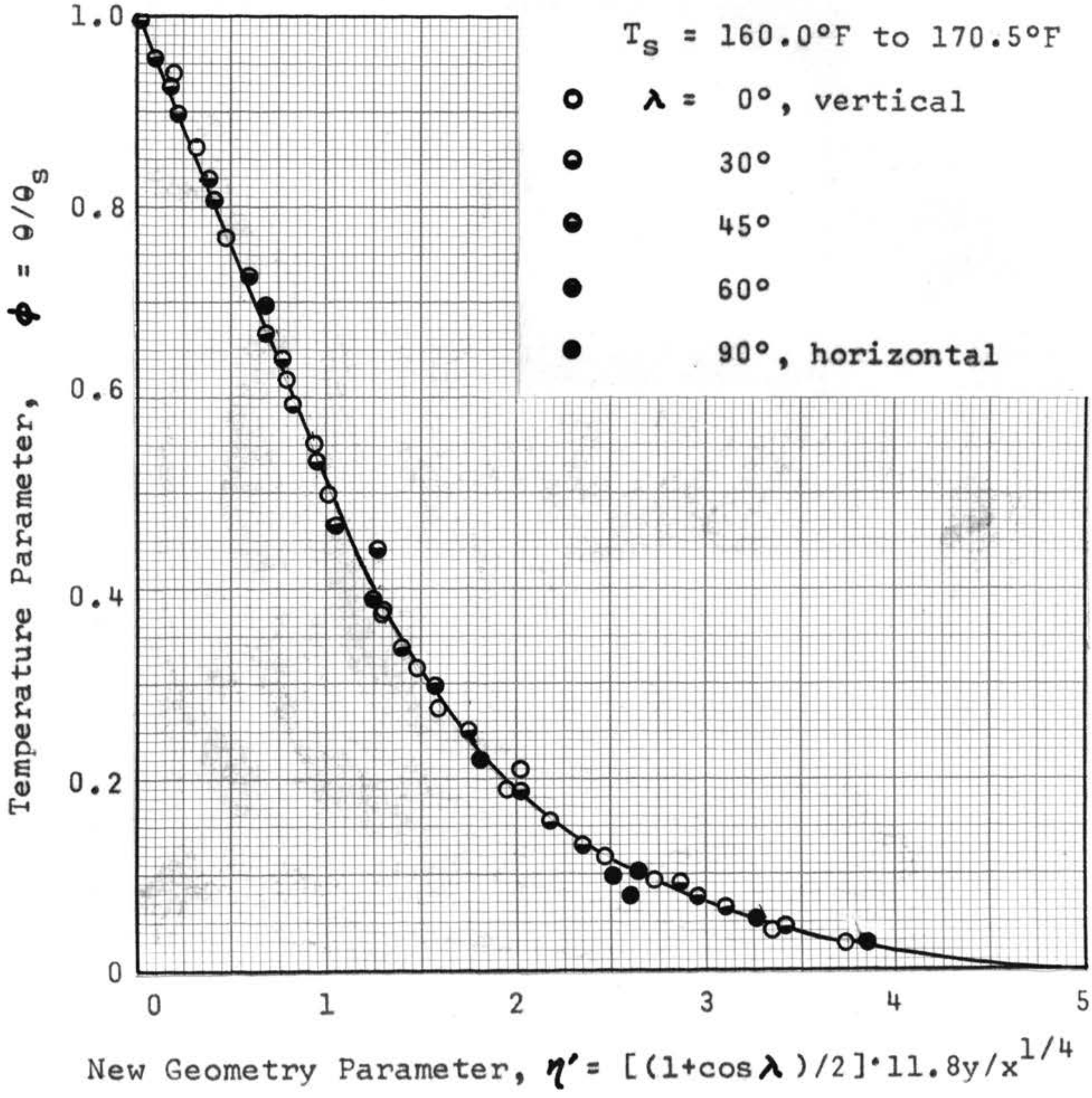

Fig. 16. Dimensionless Temperature Profile for Laminar Free Convection on an Inclined Flat Plate for all Inclined Angles

APPENDIX 3 (B)

Free Convection Thermal Boundary Layer Data

λ = 0°, vertical

T_s = 173.0°F

Boundary layer temperature	T
Room temperature	T_∞
Plate temperature	T_s
Number of turns	n

The incremental spacing between data points in the y direction is measured by the number of turns of the dial.
1 turn = 0.00298 in.

x	0.50 in.		1.00 in.			2.00 in.		
T_∞	84°F			84.5°F			85°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.182	169.0		3.220	170.5		3.233	171.0
1	3.132	167.0	1	3.177	168.8	1	3.197	169.6
	3.090	165.3		3.140	167.3		3.165	168.4
	3.048	163.6		3.107	166.0		3.135	167.1
	3.005	161.9		3.070	164.5		3.102	165.8
	2.968	160.4		3.030	162.9		3.070	164.5
5	2.738	151.1	5	2.845	155.4	5	2.908	158.0
	2.520	142.2		2.653	147.6		2.745	151.4
	2.315	133.7		2.465	139.9		2.584	144.8
	2.102	124.8		2.285	132.5		2.423	138.2
	1.930	117.6		2.120	125.5		2.271	131.9
	1.798*	112.0*		1.963	119.0		2.135	126.2
	1.670	106.6		1.840*	113.8*		2.000	120.6
	1.538	101.9		1.730	109.1		1.888	115.8
	1.476	98.2		1.620	104.4		1.793	111.8
	1.400	94.9		1.552	101.5		1.701	107.9
10	1.310	91.1	10	1.405	95.2	10	1.522	101.2
	1.250	88.4		1.335	92.1		1.430	96.2
	1.235	87.8		1.285	89.9		1.357	93.1
				1.242	88.1		1.293	90.3
							1.258	88.8
20			20			20	1.228	87.5

*The data below this point is uncertain. The readings are average values of rather wide fluctuations in some cases. The cause of these fluctuations cannot be completely explained. This is discussed in some detail in the Discussion and Recommendations section.

$\lambda = 0°$, vertical

$T_s = 173.0°F$

x	4.00 in.			8.00 in.	
T_∞	84°F			83.5°F	
n	mv.	T°F)	n	mv.	T(°F)
surface	3.257	172.0		3.270	172.5
1	3.232	170.5	1	3.245	171.5
	3.197	169.6		3.220	170.5
	3.170	168.6		3.192	169.4
	3.150	167.5		3.162	168.6
	3.122	166.6		3.157	168.0
5	2.982	161.0	5	3.040	163.3
	2.847	156.5		2.920	158.5
	2.711	150.0		2.810	154.0
	2.575	144.4		2.695	149.3
	2.443	139.0		2.580	144.6
	2.310	133.5		2.467	140.0
	2.200	128.9		2.365	135.8
	2.073	123.6		2.247	130.9
	1.968	119.2		2.150	126.9
	1.885	115.7		2.060	123.0
10	1.727	109.0	10	1.895	116.1
	1.587	103.0		1.745	109.8
	1.465	97.7		1.630	104.9
	1.398	94.8		1.530	100.6
	1.348	92.7		1.452	97.2
20	1.258	88.8	20	1.345	92.6
	1.230	87.6		1.265	89.1
	1.200	86.2		1.248	88.3
				1.230	87.4

$\lambda = 30°$

$T_s = 116°F$

x T_∞	0.50 in. 81.5°F			1.00 in. 81.5°F			2.00 in. 83°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	1.740	109.6		1.760	110.4		1.774	111.0
1	1.735	109.3	1	1.740	109.5	1	1.745	109.8
	1.713	108.6		1.725	109.1		1.730	109.1
2	1.687*	107.3*	2	1.712	108.3	2	1.721	108.8
	1.650	106.3		1.685	107.2	5	1.670	106.6
	1.635	105.1	5	1.650	105.7		1.655	105.9
5	1.600	103.6		1.624	104.6		1.620	104.4
	1.550	101.4		1.574	102.4		1.590	103.1
	1.530	100.6		1.550	101.4	10	1.533	100.7
10	1.428	96.2	10	1.467	97.4		1.470	98.0
	1.378	94.0		1.430	95.2		1.425	96.0
	1.279	89.7		1.350	92.8		1.370	93.7
	1.260	89.1		1.300	90.6			
				1.270	89.3			

*See footnote at the bottom of Page 52.

$\lambda = 30°$

$T_s = 116°F$

x / T_∞	4.00 in. 83°F		7.00 in. 85°F			10.00 in. 85°F		
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	1.770	111.0		1.850	114.2		1.870	115.0
2	1.750	110.0	1	1.830	113.4	1	1.845	114.0
	1.730	109.1	2	1.822	113.0	2	1.830	113.4
	1.715	108.4	3	1.785	111.5		1.820	113.0
5	1.690	107.4		1.785	111.5	3	1.807	112.4
	1.675	106.8	5	1.770	110.9	5	1.780	111.2
	1.638	105.2		1.740	109.6		1.763	110.6
	1.620	104.4		1.720	108.7		1.738	109.4
	1.580	102.7		1.692	107.5		1.717	108.6
	1.560	101.9		1.660	106.1		1.690	107.4
	1.530	100.6		1.624	104.6		1.667	106.4
	1.515	100.1		1.600	103.6		1.634	105.0
10	1.470	98.0		1.577	102.6		1.625	104.7
	1.440	96.7		1.545	101.2	10	1.560	101.9
	1.400	95.0		1.540	101.0		1.535	100.9
	1.360	93.2	10	1.463	97.7		1.480	98.4
	1.300	90.6		1.427	96.1		1.460	97.6
				1.418	95.8	20	1.375	93.9
				1.380	94.1			

$\lambda = 30°$

$T_S = 116°F$

x / T_∞	15.00 in. / 85.5°F		20.00 in. / 85.7°F			25.00 in. / 85.5°F		
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	1.874	115.2		1.875	115.2		1.875	115.2
1	1.865	114.8	2	1.860	114.6	2	1.845	114.0
3	1.832	113.4		1.845	114.0		1.838	113.7
	1.814	112.7	5	1.820	113.0	5	1.824	113.2
5	1.795	111.9		1.803	112.2		1.803	112.2
	1.775	111.0		1.780	111.2		1.780	112.2
	1.755	110.2		1.760	110.4		1.766	110.6
	1.740	109.6		1.730	109.1		1.740	109.6
	1.725	108.9		1.708	108.2		1.715	108.5
10	1.687	107.3		1.690	107.4		1.690	107.4
	1.657	106.0	10	1.670	106.6	10	1.635	105.1
20	1.580	102.7		1.610	104.0		1.595	103.3
	1.480	98.4		1.540	101.0		1.540	101.0
	1.410	95.4		1.520	100.1		1.525	100.3
			20	1.440	96.7	20	1.450	96.9
							1.400	95.0

$\lambda = 30°$

$T_s = 168.8°F$

x T_∞	0.25 in. 89°F			0.50 in. 89°F			1.00 in. 89°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.030	162.9		3.045	163.5		3.060	164.1
1	2.980	160.9	1	3.000	161.7	1	3.015	162.3
	2.935	159.1		2.937	159.2		2.966	160.3
	2.890	157.2		2.890	157.2		2.930	159.1
	2.830	155.1		2.859	156.0		2.910	158.1
	2.774	152.6		2.820	154.4		2.882	157.1
	2.757	151.9		2.785	153.0	2	2.835	155.0
2	2.720	150.4	2	2.771	152.4		2.789	153.2
	2.683	148.8		2.718	150.3		2.740	151.2
	2.624	146.4		2.649	147.4		2.714	150.1
	2.575	144.4		2.590	145.0		2.687	149.0
	2.525	142.4		2.544	143.2	5	2.573	144.3
5	2.390	136.8	5	2.448	139.2		2.450	139.0
	2.298	133.0*		2.340	134.8		2.310	133.5
	2.190	128.5		2.238	130.5		2.225	130.0
	2.090	124.2		2.132	126.0*		2.125	125.2
	1.985	119.9		2.040	122.2		2.020	121.4
	1.900	116.3		1.940	118.0	10	1.830	113.4
10	1.740	109.6		1.845	114.0		1.690	107.4
	1.570	102.3	10	1.650	105.7		1.597	103.4
	1.460	97.6		1.510	99.7		1.527	100.4
	1.390	94.5		1.448	97.0		1.471	98.0
20	1.324	91.7		1.400	95.0		1.400	95.0
	1.305	90.9		1.365	93.4		1.325	91.7
			20	1.320			1.320	91.6

*See footnote at the bottom of Page 52.

$\lambda = 30°$

$T_s = 168.8°F$

x / T_∞	2.00 in. 89°F			3.00 in. 89°F			5.00 in. 89°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.080	164.9		3.116	166.4		3.116	166.4
1	3.032	163.0	1	3.055	163.9	1	3.055	163.9
	3.009	162.1		3.030	162.9		3.048	163.6
	2.975	160.7		3.000	161.7		3.031	163.0
	2.950	159.7		2.978	160.8		3.016	162.3
	2.930	158.9	2	2.930	159.1		2.991	161.4
2	2.880	156.9	3	2.851	155.7	3	2.922	158.6
	2.840	155.2		2.800	153.6		2.867	156.3
	2.795	153.5		2.748	151.4		2.824	154.6
	2.755	151.8		2.701	149.6		2.745	151.4
	2.720	150.4		2.657	147.8		2.710	150.0
5	2.620	146.2	5	2.566	144.0	5	2.600	145.4
	2.510	141.8		2.463	139.8		2.510	141.8
	2.405	137.5		2.373	136.1		2.425	138.3
	2.300	133.1		2.267	131.7		2.338	134.7
	2.190	128.5		2.160	127.2		2.220	129.8
	2.110	125.1	10	2.040	122.2		2.153	127.0
	2.014	121.1		1.850	115.2		2.075	123.7
	1.950	118.4		1.721	109.2	10	1.940	118.0
10	1.802	112.2		1.650	105.7		1.780	111.2
	1.670	106.6		1.580	102.7		1.680	107.0
	1.560	102.1	15	1.440	96.7		1.580	102.7
	1.480	98.4		1.335	92.1		1.522	100.2
	1.420	95.8		1.330	91.9		1.474	98.1
	1.368	93.6					1.440	96.7
	1.335	92.1					1.371	93.7
	1.315	91.2					1.350	92.8
	1.300	90.7						

$\lambda = 30°$

$T_s = 168.8°F$

x	8.00 in.			11.00 in.			12.00 in.	
T_∞	89°F			89°F			87.5°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.125	166.7		3.125	166.7		3.125	166.7
1	3.100	165.7	1	3.100	165.7	1	3.100	165.7
	3.076	164.8		3.076	164.8		3.076	164.8
	3.046	163.3		3.050	163.8		3.050	163.8
2	2.988	161.2		3.025	162.8		3.030	162.9
	2.935	159.1	2	2.973	160.4	2	2.999	161.7
	2.890	157.2		2.945	159.5	3	2.948	159.6
	2.860	156.0	4	2.877	156.7		2.900	158.3
4	2.805	153.8		2.816	154.2		2.853	155.8
	2.740	151.2		2.760	152.0		2.790	153.2
	2.665	148.1		2.700	149.6		2.760	152.0
	2.590	145.0	5	2.630	146.7	5	2.640	147.1
5	2.500	141.4		2.550	143.4		2.516	142.0
	2.420	138.1		2.480	140.6		2.400	137.2
	2.350	135.2		2.420	138.1		2.305	133.3
	2.280	132.2		2.340	134.8		2.190	128.4
	2.208	129.2		2.270	131.8		2.105	124.9
	2.130	126.0		2.180	128.1		2.036	122.0
	2.050	122.6		2.110	125.1		1.975	119.5
	1.985	120.1		1.985	122.1	10	1.840	114.2
10	1.870	115.0	10	1.925	117.4		1.755	110.2
	1.760	110.4		1.800	112.1		1.670	106.6
	1.650	105.7		1.720	108.7		1.610	104.0
	1.580	102.7		1.610	104.0		1.550	101.4
	1.530	100.6		1.550	101.4	20	1.440	96.7
	1.480	98.4		1.500	99.2		1.350	93.2
	1.455	97.3		1.455	97.3	10	1.345	92.5
	1.380	94.1		1.410	95.4			
	1.370	93.7		1.378	94.0			
				1.370	93.7			

λ = 30°

T_s = 168.8°F

x T_∞	15.00 in. 87°F			25.00 in. 85°F			26.50 in. 85°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.120	166.2		3.055	163.9		3.055	163.9
1	3.095	165.5	1	3.025	162.7	1	3.035	163.9
	3.070	164.5		2.995	161.5		3.017	162.4
	3.045	163.5	2	2.964	160.2	3	2.940	159.5
	3.035	163.1		2.945	159.5		2.914	158.2
3	2.980	160.9		2.923	158.6		2.884	157.0
	2.930	158.9		2.875	156.6		2.840*	155.2*
	2.885	157.0		2.825*	154.6*		2.800	153.6
	2.835	155.0		2.774	152.6		2.755	151.8
	2.785*	153.0*		2.738	151.1		2.725	150.6
	2.735	151.0		2.680	148.7		2.677	148.6
	2.680	148.7		2.590	145.0		2.625	146.4
	2.630	146.7		2.550	143.4	5	2.525	142.4
5	2.545	143.2	5	2.480	140.6		2.440	138.9
10	2.385	136.6		2.435	138.6		2.370	136.0
	2.247	130.9		2.407	137.4		2.300	133.1
	2.105	124.9		2.380	136.4		2.260	131.4
	1.960	118.9	10	2.260	131.4	10	2.125	125.8
	1.825	113.6		2.150	126.8		2.000	120.6
	1.710	108.2		2.055	122.8		1.875	115.2
	1.580	102.7		1.960	118.9	20	1.660	106.1
15	1.475	98.2		1.855	114.4		1.580	102.7
	1.380	94.1		1.770	110.8		1.550	101.4
			15	1.620	104.4			
				1.520	100.1			
				1.420	95.8			
				1.375	93.9			

*See footnote at the bottom of Page 52.

λ = 30°

T_s = 296°F

x T_∞	0.50 in. 86°F			1.00 in. 87°F			2.00 in. 88°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	6.290	287.1		6.290	287.1		6.390	290.8
1	6.170	282.8	1	6.170	282.8	1	6.300	287.5
	6.050	278.3		6.060	278.2		6.205	284.0
	5.930	274.0		5.950	274.8		6.110	280.6
	5.825	270.1		5.840	270.7		6.020	277.3
	5.720	266.3		5.730	266.7		5.930	274.0
	5.610	262.2		5.620	262.6	2	5.770	268.1
	5.520	258.9	2	5.410	254.8		5.630	263.0
	5.415	255.0		5.260*	249.2*		5.480	257.5
2	5.193*	246.7*		5.160	245.5		5.350	252.7
	5.000	239.5		5.025	240.4		5.230*	248.1*
	4.820	232.8		4.875	234.9		5.097	243.1
	4.690	227.8		4.640	225.9		4.950	237.7
				4.470	219.3		4.800	232.0
				4.320	213.7		4.660	226.7
				4.180	208.2		4.520	221.3
				4.040	202.9		4.380	216.0
			5	3.540	183.2		4.240	210.6
				3.315	170.3		4.100	205.1
			10	2.740	151.1	5	3.720	190.2
				2.240	130.6		3.370	176.5
				1.825	113.2		3.050	163.7
				1.600	103.6		2.825	154.6
				1.500	99.2	10	2.360	135.6
							1.960	118.9

*See footnote at the bottom of Page 52.

$\lambda = 30°$

$T_s = 297°F$

x T_∞	4.00 in. 90°F			8.00 in. 88°F			10.00 in. 87°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	6.440	292.6		6.480	294.0		6.550	296.5
1	6.360	289.7	1	6.410	291.5	1	6.480	294.0
	6.280	286.8		6.355	289.4		6.415	291.7
	6.200	283.9		6.290	287.1		6.355	289.1
	6.120	280.9		6.230	285.1		6.300	287.5
	6.040	278.0	2	6.117	280.8		6.250	285.7
2	5.820	270.0		6.030	277.7	2	6.140	281.7
	5.683	264.9	3	5.880	272.2		6.025	277.5
	5.565	260.5		5.725	266.4		5.975	275.7
	5.450	256.3		5.530	259.2		5.810	269.2
	5.340	253.3		5.345	252.4	5	5.600	262.1
	5.230	248.1		5.280	250.0		5.367	253.2
	5.124	244.1	5	4.963	238.1		5.038	240.9
5	4.720*	229.1*		4.620*	225.1*		4.660*	226.7*
	4.420	217.5		4.310	213.3		4.400	216.7
10	3.600	185.7		4.020	202.1		4.175	208.0
				3.725	190.5		3.990	200.9
				3.468	180.4		3.660	188.0
				3.279	172.9		3.375	176.7
				3.022	162.9		3.270	172.5
			10	2.645	147.3	10	2.920	158.5
				2.300	133.1		2.525	142.4
							2.260	131.4
							2.025	121.6

*See footnote at the bottom of Page 52.

λ = 30°

T_s = 297°F

x T_∞	15.00 in. 87°F			20.00 in. 86°F			25.00 in. 86°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	6.550	296.5		6.550	296.5		6.450	292.9
1	6.490	294.3	1	6.500	294.7	1	---	---
	6.430	292.2		6.450	292.9		---	---
	6.375	290.2		6.400	291.1	1/4	6.290	287.1
	6.320	288.2		6.355	289.4		6.270*	286.4*
2	6.225	284.4	2	6.250*	285.7*		6.240	285.3
	6.120	280.9		6.150	278.3		6.223	284.7
	6.070*	279.1*	5	5.900	272.9		6.223	284.7
5	5.840	270.8		5.660	264.1	1	6.165	282.6
	5.535	259.4		5.440	255.9		6.125	281.1
	5.375	253.5		5.220	247.8		6.000	276.6
	5.170	245.9		4.975	238.6			
	4.750	230.0						
	4.600	224.3						
	4.300	212.9						
	3.925	198.4						
10	3.570	184.4						
	3.120	166.5						
	2.880	156.9						
	2.600	145.4						

*See footnote at the bottom of Page 52.

λ = 30°

T_s = 407°F

x T_∞	1.00 in. 85°F			3.00 in. 85°F			7.00 in. 85°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	9.260	391.0		9.330	393.4		9.650	404.2
1	9.150	387.3	1	9.240	390.4	1	9.540	400.5
	9.050	383.9		9.150	387.3		9.430	396.8
	8.950	380.5		9.060	384.3		9.320	393.1
	8.840	376.8		8.970*	381.2*		9.200	389.0
2	8.630	369.6		8.870	377.8		9.110	386.0
	8.430*	362.7*				2	8.935	380.0
	8.230	255.8					8.730*	373.0*
	8.030	348.8					8.525	366.0
	7.830	341.9					8.330	359.3
	7.630	334.9					8.130	352.3
	7.550	332.1				5	7.730	338.3
5	7.050	314.4					7.137	317.5
	6.500	294.8					6.635	299.5
	6.090	279.9					6.200	283.9
	5.580	261.1					5.825	270.1
	5.000	239.4					5.370	253.3
	4.570	223.2						
	4.040	202.9						
	3.540	183.2						

*See footnote at the bottom of Page 52.

λ = 30°

T_S = 407°F

x / T_∞	9.00 in. 85°F			11.00 in. 85°F			15.00 in. 85°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	9.720	406.7		9.720	406.7		9.720	406.7
1	9.600	402.5	1	9.600	402.5	1	9.610	402.9
	9.485	398.7		9.485	398.5		9.510	399.5
2	9.280	391.8	2	9.280	391.8		9.415	396.3
	9.065	384.4		9.070	384.6	2	9.225	389.1
	8.860	377.5		8.870	377.8		9.050	384.0
	8.680*	371.3*		8.870	377.8		8.880	378.1
5	8.280	357	5	8.240	365.1		8.725	372.9
	7.670	336		7.745	339.0	5	8.250	356.5
	7.290	323		7.280	322.4		7.800	341.1
	6.680	301		6.850*	307.3*		7.380*	326.1*
	6.365	290		6.430	292		6.900	309.9
	5.960	275	10	5.530	259		6.430	292.1
	5.364	253		4.460	219	10	5.570	260.8
	5.000	240		3.850	195		5.050	241.3
	4.570	223		3.120	166		4.250	211.0
	4.030	203	20	2.650	148		3.730	190.8
10	3.220	171						
	2.800	154						
	2.400	137						
	1.920	117						

*See footnote at the bottom of Page 52.

$\lambda = 45°$

$T_s = 165.5°F$

x T_∞	0.50 in. 85°F			1.00 in. 85°F			2.00 in. 84.5°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	2.850	155.7		2.910	158.1		2.970	160.5
	2.825	154.6	2	2.859	156.0	2	2.920	158.5
2	2.775	152.6		2.803	153.7		2.870	156.4
	2.710	150.0		2.724	150.5		2.823	154.5
	2.650	147.5		2.690	149.1		2.800	153.6
	2.610	145.8		2.655	147.7		2.770	152.4
	2.570	144.2	5	2.525	142.4	5	2.656	147.7
5	2.438*	138.8*		2.450	139.3		2.570	144.2
	2.250	131.0		2.390	136.8		2.490	141.0
	2.125	125.8		2.180*	128.1*		2.377	136.3
	1.980	119.7		2.060	123.0		2.200	128.9
	1.760	110.4		1.940	118.0		2.107*	125.0*
	1.620	104.4		1.825	113.2		2.030	121.8
				1.710	108.2		1.965	119.1
				1.594	103.3		1.870	115.0
			10	1.470	98.0		1.770	111.2
				1.460	97.6		1.700	107.8
				1.460	97.0	10	1.610	104.0
							1.510	99.7
							1.410	95.4
							1.320	91.5
							1.290	90.2
							1.270	89.7

*See footnote at the bottom of Page 52.

$\lambda = 45°$

$T_s = 165.5°F$

x T_∞	5.00 in. 84.5°F			10.00 in. 84.5°F			14.00 in. 84.5°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.020	162.5		3.075	164.7		3.075	164.7
2	2.925	158.7	2	3.025	162.7	2	3.025	162.7
	2.885	157.0		2.985	161.1		2.987	161.2
	2.850	155.6		2.952	159.8		2.954	159.8
	2.820	154.4		2.920	158.5		2.925	158.7
	2.796	153.4		2.880	156.8		2.890	157.2
5	2.725	150.6	5	2.785	153.0	5	2.822	155.5
	2.638	147.0		2.685	148.9		2.740	151.2
	2.525	142.4		2.600	145.4		2.660	147.9
	2.450	139.3		2.550	143.4		2.580	144.6
	2.340	134.8		2.495	141.2		2.480	140.6
	2.275	132.0		2.440	138.9		2.388	136.6
	2.170*	127.7*		2.390	136.8		2.320	133.9
	2.040	122.2		2.276	132.1		2.260	131.4
	1.989	120.1		2.165	127.4		2.194	128.7
10	1.870	115.0		2.090	124.3		2.100	124.7
	1.775	111.0		2.010	121.0		2.050	122.6
	1.680	107.0	10	1.850	114.2		2.000	120.6
	1.535	100.9		1.740*	109.6*	10	1.880	115.5
	1.425	96.0		1.633	105.0		1.750	110.0
	1.390	94.0		1.535	100.9		1.640	105.3
	1.360	93.2		1.480	98.4		1.550*	101.4*
				1.410	95.4		1.495	99.0
				1.350	92.9		1.460	97.6
				1.330	92.0		1.420	95.8
				1.300	90.6	20	1.330	92.0

*See footnote at the bottom of Page 52.

$\lambda = 45°$

$T_s = 165.5°F$

x T_∞**	18.00 in. 83°F			25.00 in. 82°F	
n	mv.	T(°F)	n	mv.	T(°F)
surface	3.075	164.7		3.057	164.0
2	3.033	163.0	2	3.025	162.7
	2.983	161.0		3.000	161.7
	2.940	159.3		2.968	160.4
	2.916	158.3		2.935	159.1
5	2.846*	155.4*		2.910	158.1
	2.760	152.0	5	2.827	154.7
	2.680	148.7		2.760*	152.0*
	2.625	146.5		2.700	149.6
	2.575	144.4		2.640	147.1
	2.510	141.8		2.570	144.2
	2.430	138.5		2.500	141.4
	2.360	135.6		2.435	138.7
	2.280	132.3		2.377	136.3
	2.220	129.8		2.110	125.1

*See footnote at the bottom of Page 52.

**The ambient air temperature fluctuated noticeably.

λ = 45°

T_s = 291.5° -288°F

x T_∞	1.00 in. 81°F			2.00 in. 81.5°F			4.00 in. 82.5°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	6.150	282.0		6.205	284.0		6.205	284.0
2	5.935	274.2	2	6.110	281.0	2	6.110	281.0
	5.820	270.0		5.930	274.0		5.980	275.8
	5.630	263.0		5.794	269.0		5.780	272.0
	5.469	257.0		5.660	264.1		5.690	265.2
	5.350	252.7		5.525	259.1		5.585	261.3
	5.227	248.0		5.445	256.1		5.490	257.8
	5.080*	242.5*		5.350	252.6	5	5.200	247.0
	4.934	237.0	5	4.987	239.0		4.960	238.0
5	4.640	225.9		4.643	226.0		4.670	227.0
	4.225	210.0		4.300	212.9		4.329	214.0
	3.810	193.9		3.975	200.3		4.018*	202.0*
	3.480	180.9		3.635	187.0		3.850	195.5
	3.120	166.5		3.340	177.7		3.508	183.0
	2.908	158.0		3.040	163.3		3.220	170.5
	2.620	146.2		2.760	152.0		2.918	158.0
	2.460	139.7		2.460	139.7		2.614	146.0
	2.250	131.0		2.178	128.0	10	2.346	135.0
	2.060	123.0	10	1.990	120.1		2.080	124.1
10	1.660	106.1		1.810	112.6		1.820	113.0
	1.550	101.4		1.700	107.8		1.770	110.8
	1.400	95.0		1.600	103.6	20	1.550	101.4
20	1.330	91.9		1.510	99.7		1.370	93.7
				1.450	97.1			

*See footnote at the bottom of Page 52.

$\lambda = 45°$

$T_s = 291.5°$ to $288°F$

x	8.00 in.			12.00 in.			15.00 in.	
T_s								
T_∞	83°F			84°F			85°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	6.260	286.0		6.375	290.2		6.400	291.1
2	615.0	282.0	2	6.225	284.8	2	6.310	287.9
	6.020	277.3		6.140	281.7		6.215	284.4
	5.920	273.7		6.040	278.0		6.135	281.5
	5.820	270.0		5.930	274.0		6.050	278.4
	5.725	266.4		5.850	271.1		5.970	275.5
	5.640	263.3		5.800	269.3	5	5.745	266.8
5	5.352	252.7	5	5.577	261.0		5.457	256.5
	5.045	241.2		5.324	251.7		5.220	247.8
	4.820	232.7		5.035	240.8		4.925	237.3
	4.540	222.1		4.810	232.3		4.720	229.1
	4.277*	212.0*		4.570	223.1		4.410	217.1
	4.018	202.0	10	4.070*	204.0*		4.260	211.3
	3.740	191.1		3.680	188.8		3.993	201.0
	3.485	181.1		3.300	173.7		3.550*	183.7*
10	3.150	167.7		2.890	157.2		3.240	171.3
	2.825	154.6		2.589	145.0	10	2.910	158.0
	2.443	139.0		2.250	131.0		2.640	147.1
	2.178	128.0		1.916	117.0		2.460	139.7
	1.880	115.5		1.770	110.8		2.250	131.8
	1.625	104.7		1.680	107.0		1.930	117.6
	1.540	101.0		1.540	101.0		1.810	112.6
	1.460	97.6	20	1.400	95.0		1.615	104.2
20	1.378	94.0		1.360	93.2			

*See footnote at the bottom of Page 52.

λ = 60°

T_s = 165.5° to 170°F

x		0.50 in.			1.00 in.			2.00 in.
T_s		82°F			83°F			84°F
T_∞		165.5°F			166°F			167.5°F
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.050	163.7		3.070	164.5		3.070	164.5
2	2.970	160.5	2	---	---	1.5	3.040	163.3
	2.900	157.7		2.975	160.7	2	2.985	161.1
	2.835	155.0		2.940	159.3		2.935	159.1
	2.778	152.3		2.847	156.6		2.884	157.0
	2.710	150.0		2.810	154.0		2.825	154.5
	2.650	147.5		2.750	151.6		2.785	153.0
5	2.515	142.0		2.705	149.8	5	2.700	149.6
	2.385*	136.6*	5	2.614	145.0		2.620	146.2
	2.255	131.2		2.506	141.6		2.530	142.6
	2.120	125.6		2.394	137.0		2.440	138.9
	1.990	120.1		2.298	133.0		2.340	134.8
	1.900	116.3		2.190	128.5	10	2.100	124.7
	1.850	114.2		2.090	124.3		1.950	118.4
10	1.680	107.0	10	1.940	118.0		1.830	113.4
	1.540	101.0		1.795	111.9		1.710	108.2
				1.655	108.7		1.600	103.6
				1.563	102.0	20	1.440	96.7
				1.450	96.9		1.375	93.9
			20	1.375	93.9			
				1.370	93.7			

*See footnote at the bottom of Page 52.

$\lambda = 60°$

$T_s = 165.5°$ to $170°F$

x T_s T_∞	4.00 in. 85°F 168°F		8.00 in. 87°F 170°F			12.00 in. 87°F 170°F		
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.075	164.7		3.165	168.4		3.180	168.9
2	3.025	162.7	2	3.085	164.5	1.5	3.150	167.7
3.3	2.940	159.3		3.040	163.3	3	3.070	164.5
	2.870	156.4	5	2.960	160.1		3.020	162.5
	2.800	153.6		2.882	156.9		2.975	160.6
5	2.755	151.8		2.810	154.0	5	2.903	157.8
	2.650	147.5		2.711	150.0		2.840	155.2
	2.560	143.8		2.635	146.9		2.780	152.8
	2.490	141.0		2.560	143.8		2.700	149.6
	2.410	137.7		2.480	140.6		2.620	146.3
10	2.260*	131.4*		2.420	138.1		2.540	143.0
	2.108	125.0		2.350	135.2		2.470	140.1
	1.970	119.3		2.280	132.0		2.400	137.2
	1.850	114.2	10	2.120	125.6	10	2.240	130.6
	1.680	107.0		1.990	120.1		2.130	126.0
20	1.475	98.2		1.850	114.2		2.000	120.6
	1.378	94.0		1.760	110.4		1.920	117.2
	1.300	90.6		1.680	107.0		1.810	112.6
				1.600	103.6		1.725	108.9
				1.520	100.1		1.645	105.5
			20	1.450	97.1	20	1.520	100.1
				1.420	95.8		1.450	97.1
							1.370	93.7

*See footnote at the bottom of Page 52.

λ = 60°

T_s = 165.5° to 170°F

x	16.00 in.			20.00 in.			25.00 in.	
T_s	87°F			87°F			88°F	
T_∞	170°F			170°F			170°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.175	168.7		3.175	168.7		3.175	168.7
3	3.120	166.5	3	3.127	166.8	3	3.130	167.0
	3.070	164.5		3.083	165.0		3.085	165.1
5	3.018	162.4		3.040	163.3		3.040	163.3
	2.952	159.8	5	2.940	160.5	10	2.920	158.5
	2.840	155.2		2.900	157.8		2.785	153.0
	2.765	152.2		2.835	155.0		2.680	148.7
	2.680	148.7		2.770	152.4		2.520	142.2
	2.605	145.6		2.700	149.6		2.420	138.1
	2.510	141.8		2.630	146.7		2.310	133.6
	2.425	138.3		2.560	143.9		2.185	128.3
	2.360	135.6		2.500	141.4	20	2.000	120.6
10	2.230	130.2		2.445	139.1		1.820	113.0
	2.100	124.7	10	2.290	132.7		1.720	108.7
	2.000	120.6		2.175	123.7			
	1.880	115.5		2.075	123.7			
20	1.725	108.9		2.000	120.6			
	1.620	104.4		1.910	116.8			
	1.470	98.1	20	1.730	109.1			
				1.600	103.6			
				1.500	99.2			

λ = 60°

T_s = 294°F

x T_∞	0.50 in. 86°F			1.00 in. 85.5°F			2.00 in. 85°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	6.170	282.8		6.170	282.8		6.170	282.8
2	6.10	277.1	2	6.030	277.7	2	6.050	278.3
	5.845	270.9		5.905	273.1		5.932	274.1
	5.680	264.8		5.775	268.3		5.815	269.8
	5.520*	258.9*		5.640	263.3		5.700	265.6
	5.350	252.6		5.515	258.7		5.585	261.3
	5.200	247.0		5.375*	253.5*		5.470	257.0
5	4.850	233.9		5.250	248.9		5.350	252.6
	4.450	218.7	5	4.880	235.0	5	5.040*	241.0*
	4.125	206.1		4.550	222.6		4.740	229.6
10	3.680	188.8		4.250	211.0		4.440	218.2
	3.132	167.0		4.000	201.3		4.150	245.1
							3.850	195.4
						10	3.350	175.8
							2.910	158.1

*See footnote at the bottom of Page 52.

λ = 60°

T_s = 294°F

x	4.00 in.			8.00 in.			12.00 in.	
T_∞	85°F			85°F			84.5°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	6.270	286.4		6.400	291.1		6.470	293.6
2	6.120	281.1	2	6.300	287.5	2	6.380	290.4
	6.000	276.6		6.210	284.2		6.287	287.0
	5.900	272.9		6.090	279.9		6.180	283.1
	5.770	268.1		6.008	276.9		6.100	280.2
	5.670	264.5		5.895	272.7		6.010	277.1
	5.570	260.8		5.820	270.0		5.920	273.6
	5.460	256.7		5.725	266.5		5.825	270.1
5	5.160	245.5	5	5.460	256.6	5	5.590	261.5
	4.860	234.2		5.220	247.8		5.440	256.1
	4.570*	223.2*		4.975	238.6		5.215	247.6
	4.280	212.1		4.740	229.6		4.940	237.2
	4.000	201.3		4.460	219.0		4.725	228.9
	3.740	191.1		4.230	210.2		4.500	220.6
	3.480	181.1		3.980	200.5		4.300	212.9
	3.240	171.3		3.720	190.3		4.060	203.6
	3.075	164.7		3.559	184.0		3.820	193.7
	2.850	155.6		3.407	178.0		3.590	185.2
	2.570	144.2	10	2.950	159.7	10	3.210	170.1
10	2.270	131.8		2.600	145.4		2.910	158.1
	2.025	121.6		2.275	232.0		2.610	145.8
	1.780	111.2		2.060	123.0		2.330	133.9
	1.700	107.8		1.860	114.6		2.170	127.7
	1.700	107.8		1.725	108.9	20	1.720	108.7
			20	1.570	102.3		1.525	100.3
				1.470	98.0			

*See footnote at the bottom of Page 52.

λ = 60°

T_s = 294°F

x T_∞	16.00 in. 85°F			20.00 in. 84°F			25.00 in. 83°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	6.470	293.6		6.470	293.6		6.370	290.0
2	---	---	2	6.400	291.1	2	6.290	287.1
	6.325	288.4		5.325	288.4		6.215	284.4
	6.225	284.4		6.245	285.5		6.140	281.7
	6.130	281.3		6.165	282.6		6.055	278.4
	6.060	278.7		6.080	279.5		5.980	275.8
	5.975	275.4		6.000	276.6		5.910*	273.3*
	5.825	270.2	5	5.800	269.2	5	5.725	266.5
5	5.625	262.4		5.600	261.9		5.480	257.4
6	5.370	253.4		5.415	255.0		5.307	251.0
5	5.170	245.2		5.220	247.7		5.115	243.8
	4.910	236.1		5.010	239.8		4.860	234.2
	4.735	229.1		4.730	229.3		4.670	227.0
	4.500	220.6	10	4.270	211.7	10	4.250	211.0
	4.310	213.3		3.890*	197.0*		3.940	199.0
	4.060	203.6		3.540	183.2		3.475	180.7
	3.760	192.1		3.180	168.9		3.200	169.7
	3.580	184.8		2.860	156.0		2.910	158.1
10	3.310	174.1		2.530	142.6		2.550	143.4
	3.000*	161.7*		2.230	130.0		2.320	134.0
	2.660	147.9		2.110	125.1			
	2.375	136.2						
	2.070	123.5						
20	1.880	115.4						

*See footnote at the bottom of Page 52.

λ = 90°

T_s = 170.5°F

x T_∞	0.25 in. 88°F			0.50 in. 88°F	
n	mv.	T(°F)	n	mv.	T(°F)
surface	3.085	165.1		3.085	165.1
5	2.940	159.3	2	3.030	162.9
	2.800	153.6		2.975	160.7
	2.660	147.9		2.925	158.7
	2.530	142.4		2.875	156.7
	2.400	137.2		2.830	154.8
	2.290	132.7		2.775	152.7
10	2.020	121.4		2.730	150.8
	1.850*	114.2*		2.675	148.5
	1.720	108.7	5	2.570*	144.2*
	1.560	101.9		2.440	138.9
	1.480	98.4		2.300	133.1
	1.450	97.1	10	2.125	125.8
	1.400	95.0		2.000	120.6
	1.375	93.9		1.850	114.2
				1.725	108.9

*See footnote at the bottom of Page 52.

$\lambda = 90°$

$T_s = 170.5°F$

x T_∞	2.50 in. 88°F			6.00 in. 88°F			13.50 in. 87°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	3.144	167.5		3.220	170.5		3.220	170.5
5	3.060	164.1	5	3.155	167.9	5	3.155	167.1
	2.985	161.1		3.080	164.9		3.080	164.9
	2.900	157.7		3.005	161.9		3.005	161.9
	2.815	154.2		2.930	158.9		2.935	159.1
20	2.500	141.4		2.870	156.4		2.870	156.4
	2.250	131.0		2.800	153.6		2.805	153.8
	2.000	120.6		2.730	150.8		2.755	152.2
	1.800	112.1		2.659	147.8		2.710	150.0
	1.660	106.4		2.595	145.2		2.670	148.3
	1.520	100.1		2.530	142.4		2.620	146.2
				2.470	140.1		2.570	144.2
				2.410	137.7		2.516	142.0
				2.355	135.4		2.467	140.0
				2.305	133.7		2.410	137.7
				2.225	131.0		2.355	135.4
				2.200	128.9	10	2.250	131.0
			20	1.910	116.8		2.130	126.0
				1.740	109.6		2.020	121.4
				1.625	104.7		1.910	116.8
							1.810	112.6
						20	1.720	108.7
							1.625	104.6
							1.520	100.1

$\lambda = 90°$

$T_s = 289°F$

x T_∞	2.00 in. 87°F			6.00 in. 87°F			13.00 in. 87°F	
n	mv.	T(°F)	n	mv.	T(°F)	n	mv.	T(°F)
surface	5.970	275.5		6.320	288.2		6.320	288.2
2	5.850	271.1		6.220	284.6		6.200	283.8
	5.740	267.0		6.060	278.8		6.100	282.2
	5.650	263.7		5.940	274.4		6.025	277.5
	5.550*	260.0*		5.875*	272.0*		5.950	274.8
5	5.320	251.5		5.760	267.8	5	5.750	267.4
	5.100	243.2	5	5.510	258.5		5.540	259.6
	4.940	237.2		5.320	251.5		5.325*	251.6*
	4.740	229.6		5.120	244.0		5.140	244.7
	4.530	221.7		4.920	236.5		4.970	238.4
10	4.100	205.1		4.730	229.3	10	4.630	226.5
				4.530	221.7		4.290	212.5
				4.380	216.0		4.000	201.3
				4.150	207.0		3.740	191.1
				3.920	198.2		3.480	180.9
							3.100	165.7
							2.850	155.6
							2.630	146.7
						20	2.230	130.1
							1.740	109.5
							1.540	101.0

*See footnote at the bottom of Page 52.

APPENDIX 3

(C) Sample Calculations

A calculation is shown for the plate angle, $\lambda = 45°$, at a position above the leading edge, x = 10 in. The plate surface temperature is $T_s = 164°F$, and the surrounding fluid temperature is $T_\infty = 84°F$. The boundary layer position is chosen as y = 0.03 in. where the boundary layer temperature is indicated by the thermocouple to be T = 156.7°F.

Now, the temperature parameter, ϕ, becomes

$$\phi = (T - T_\infty)/(T_s - T_\infty) = (156.7 - 84)/(164 - 84)$$

$$\phi = 0.909$$

and the boundary layer parameter, η, becomes

$$\eta = 11.8y/x^{1/4} = 11.8(0.03)/(10)^{1/4}$$

$$\eta = 0.199$$

The new boundary layer parameter, η', becomes

$$\eta' = [(1 + \cos\lambda)/2](11.8)y/x^{1/4}$$

$$\eta' = [(1 + \cos 45°)/2](11.8)(0.03)/(10)^{1/4}$$

$$\eta' = 0.170$$

In this manner a set of data is obtained at x = 10 in. for all y values.